# THIRD BIENNIAL PLAINS AQUATIC RESEARCH CONFERENCE: Proceedings

Editor: M. Douglas Scott

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# THIRD BIENNIAL PLAINS AQUATIC RESEARCH CONFERENCE

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# FOREWORD

## HISTORY AND PURPOSE OT THE PLAINS AQUATIC RESEARCH CONFERENCE

During 1978, an informal group, primarily from the prairie provinces of Alberta, Manitoba, and Saskatchewan, decided to start a biennial conference devoted to water research and management in the plains environments of North America. In 1979, immediately after the first conference, the organization was formalized as the Plains Aquatic Research Group. The Group is affiliated with the Canadian Plains Research Center, at the University of Regina, Regina, Saskatchewan, which assures continuity in its administration.

The Plains Aquatic Research Group (PARG) has sponsored two conferences to date. The first was in 1979, at the University of Regina, and the 1981 conference was held at the University of Calgary. After the second conference, it was decided that more interaction with the prairie states was desirable. Consequently, Montana State University, on the western edge of the United States Northern Great Plains, was selected to host the third Biennial Plains Aquatic Research Conference (PARC), in 1983.

A major principle underlying these conferences was that they would facilitate the exchange of ideas between people working in a variety of professions dealing with water research and management. It was hoped that, by bringing together people with diverse educational backgrounds, such as biology, engineering, geography, hydrology, and political science, participants could gain a more holistic concept of the types of interactions that must take place when any water resource is managed, or mismanaged. We have tried to maintain this princple at the third conference in Bozeman. The only restriction placed on the conference participants has been that papers presented must relate in some way to water resources in the plains (prairie) environment.

As in past PARC meetings, the 1983 conference features two major types of material - technical papers and a Special Symposium. The technical papers in various water-related disciplines are intended to provide for communication among research specialists and people who work with water resources in an applied sense. The Special Symposium is designed to generate a 'state-of-the-art' discussion on one particular water management issue in the plains environment that is of current high importance.

This year's technical papers are grouped into four sessions, including: Biological Sciences; Hydrology; Reclamation of Water Resources; and Water Resource Management and Policy. The Special Symposium topic this year is "International Management of Water Resources," which seems especially appropriate since the conference host state, Montana, has the unique privilege of bordering three provinces. Representatives of the governments of several provinces and states have been brought together in this Symposium to provide an overview of the current international controversies and cooperation that have arisen out of our attempts to manage waters that cross political, but not necessarily ethnic, boundaries. This probably is the first time that so many different provincial and state government representatives have been brought together to discuss this topic outside Ottawa or Washington. We hope that further cooperation in managing water between governments may be facilitated by the Symposium.

This Third Biennial PARC meeting is the first one where the complete technical papers and Symposium presentations are being published in a Conference Proceedings, under the auspices of the Canadian Plains Research Center. Past conferences have published the Special Symposium papers only. Judging from the enthusiasm shown by participants for having their papers published, we may expect to see all technical papers published in future conferences. It certainly seems worthwhile to secure a complete written record of what took place at our conference, so that others may learn from, and critique, our methods used and conclusions reached in studying and managing so important a natural resource as water.

M. Douglas Scott
1983 PARC Conference Chairman
and Editor of Proceedings

## ACKNOWLEDGMENTS

A number of people have been responsible for the numerous preparatory details involved in holding this Third Biennial meeting of the Plains Aquatic Research Conference. We would especially like to extend our appreciation to the Canadian Plains Research Center. In particular, the Director of the CPRC, Dr. M. Evelyn Jonescu, has generously given her time and the facilities of the Center to help organize the Conference Proceedings, with the able assistance of the meeting committee. We are grateful to Gillian Wadsworth Minifie and Lorraine Nelson, both of the CPRC, who have dealt with the details of preparing and editing this first complete Conference Proceedings. Without their timely attention to numerous items, the proceedings would not have been possible.

For the development of a valuable program of technical topics, we wish to thank the Technical Review Committee, composed of the following:

Biology - Dr. Don T. Waite
Hydrology - Dr. Stephan G. Custer
Water Management - Dr. Howard Peavy and Dr. James Heimbach
Reclamation - Dr. Douglas Dollhopf
Policy - Dr. John Alwin and Dr. Joseph M. Ashley

These people devoted a great deal of time and effort in the evaluation of program submissions.

Our thanks also are extended to those who presented papers, offered their technical knowledge in the plenary sessions, and contributed to technical discussions throughout the meeting.

Local preparations for holding a conference such as PARC are always detailed and time-consuming. We would like to express our appreciation to the following local Committee Chairmen:

Treasurer and Registrar - Ann W. Parker
Meals and Banquet - Dr. James A. Heimbach
Campus Facilities - Dr. John Alwin
Publicity - Dr. Joseph M. Ashley and Dr. John Alwin

Members of the current Plains Aquatic Research Group Executive Committee are:
Dr. Don T. Waite (Group Chairman)
Dr. Brian R. Hammond (Secretary)
Dr. Jan M. Barica
Dr. Bruce L. Baker
Dr. M. Douglas Scott (1983 Convener)
Ron P. Johnston
Dr. W. Lyle Lockhart

Many other people, who are not mentioned specifically, have contributed to the meeting and we extend out thanks to them all for their assistance.

## SESSION I: BIOLOGICAL SCIENCES

Chairman
Dr. Don T. Waite
Environmental Protection Service
Environment Canada
Regina, SK

# THE EFFECT OF TERRESTRIAL HERBICIDES
# ON THE
# PRODUCTIVITY OF AGRICULTURAL STREAM COMMUNITIES

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## ABSTRACT

Artificial streams colonized from a spring and an agriculturally impacted stream were used to assess the effect of 0.1, 1 and 10 ppm of the terrestrial herbicides atrazine, trifluralin, MSMA and paraquat on the productivity of periphyton. In an attempt to demonstrate the development of herbicide resistance, in each experiment 16 of the 32 streams were colonized by algae in the presence of 0.01 ppm of the test herbicide, and the other 16 streams remained uncontaminated during colonization. Productivity was determined by open water oxygen methods. Trifluralin had no important effect on productivity. Significant productivity depression lasting up to three weeks was caused by 1 and 10 ppm atrazine and by 10 ppm MSMA in experiments with both the spring and stream algae. The 0.01 ppm atrazine treatment also caused a slight but detectable photosynthetic depression. Paraquat had no effect on the spring community but severely depressed the photosynthesis of the stream algae. There was no evidence of induced herbicide resistance. This datum and the greater sensitivity of the stream algae to paraquat imply that the rapid development of herbicide resistance by stream algae may be uncommon.

The United States Federal Environment Pesticide Control Act of 1972 requires that pesticides which are used as directed should not endanger non-target communities (Ware, 1975). Since agricultural streams are runoff conduits, the determination of the effects of herbicides on their primary producer organisms should be an important research goal. Nevertheless, there is almost no information available on the effect of herbicides on stream algae. The literature concerning the influence of herbicides on algae (reviewed in Butler, 1977 and Brown, 1978) mainly reports the effect of herbicide application to single-species cultures. Field studies usually report the reactions of planktonic pond algae to weed-control measures. Often, these investigators report how the phytoplankton and *Chara* benefit from the destruction of macrophytes (Fish, 1966; *Way et* al., 1971; Brooker and Edwards, 1973a and b; Ellis et al., 1976; Peverly and Johnson, 1979; Boyle, 1980). In addition, water quality surveys usually find that herbicide contamination in rivers is widespread but at very low concentrations. For example, atrazine, one of the most heavily used and studied herbicides, is usually found to be present at maximum concentrations in the low ppb range (Richard et al., 1975; Frank and Siron, 1979; Wu, 1981). These results combine to downgrade the apparent importance of herbicide effects on stream algae.

Nevertheless, it is possible that stream algal communities are being adversely affected by herbicide runoff. Maximum herbicide concentrations in runoff in the low ppm range have been documented for atrazine (Hall et al., 1972; Kadoum and Mock, 1978; Roberts et al., 1979), MSMA (Wauchope et al., 1977) and paraquat (Smith et al., 1979), and algae close to a runoff entry point would therefore experience stress far greater than the whole-stream concentration would indicate. Also, de Noyelles et al. (1982) demonstrated that 0.5 and 0.02 ppm atrazine caused detectable productivity depression and shifts of species dominance in experimental ponds, implying that there is a potential for adverse herbicide impact on stream algae also. Virtually the only direct information on the effect of herbicides on stream algae was reported by Moorhead (1981), a former graduate student in RJK's laboratory. He reported a significantly lower net community productivity in artificial streams that had been treated with 1 and 10 ppm atrazine.

We have just completed a two-year study which assessed the effects of the herbicides atrazine (2-chloro-4-(ethylamino)-6-(isopropylamino)-s-triazine), trifluraln (α, α, α-trifluoro-2,6-dinitro-N, N-dipropyl-p-toluidine), MSMA (monosodium methanearsonate) and paraquat (1,1'-dimethyl-4,4'-bipyridylium cation) on complex algal communities in artificial streams. This report emphasizes the effects of the herbicides on productivity as determined with open-water oxygen methods.

To assess the long-term development of herbicide resistance, we used two sources of water and colonizing algae: Minter Spring (1981 experiments and the Little Brazos river (1982 experiments). Both waters are in Brazos County, central Texas. Minter Spring emerges from a concrete standpipe in a pasture, is anoxic, has a nearly constant temperature of 21°C, and has no known history of exposure to herbicides. The Little Brazos, on the other hand, runs through an intensively farmed cotton and sorgham region and is heavily influenced by agricultural runoff. Our expectation was that the Little Brazos algae, which have probably been exposed many times to herbicides in the past, would show relatively more resistance to herbicide toxicity. To facilitate comparison between the two sets of results, we conducted experiments on each herbicide during the same seasonal period in 1981 and 1982: atrizine in April-May, trifluralin in June-July, MSMA in August-September and paraquat in October-November.

## METHODS AND MATERIALS

The 32 artificial streams were small recirculating systems, each 2.44 m long. A wooden framework was lined with plastic and stream-worn pebbles and filled with water from either Minter Spring or the Little Brazos to a depth of 4 cm. An electric pump propelled water through the channel at an average rate of 3 cm $sec^{-1}$. A translucent fiberglass cover protected the streams against rain, wind and evaporation, and any loss of water was replaced by an automatic reservoir filled with source water. We placed the streams on a flat roof on the Texas A&M University campus.

We conducted a total of eight experiments: one for each herbicide using Minter Spring algae in 1981, and one for each herbicide using Little Brazos algae in 1982. Each experiment consisted of a three or four week colonization period, herbicide application, and a three week follow-up period. Our experimental design was a balanced factorial arrangement of "chronic" and "acute" treatments. For the chronic treatments, we allowed 16 of the 32 streams in each experiment to colonize with algae in the presence of 0.01 ppm of the test herbicide in the water. The other 16 colonized in uncontaminated water. This was an attempt to demonstrate the development of herbicide resistance in the chronically-exposed streams. The acute treatments were the application (after three or four weeks of colonization) of 0, 0.1, 1 and 10 ppm active ingredient of the test herbicide to eight streams each. Thus there were four streams in each chronic x acute treatment combination.

Productivity was measured by open-water oxygen methods (Odum, 1956; Owens, 1974) which correct the rise and fall of dissolved oxygen in a stream for exchange with the atmosphere and then use the corrected changes as an estimate of net community productivity. We determined the reaeration coefficient by deoxygenating a source water sample with 0.04 mg sodium bisulfite and a few crystals of cobaltous chloride per L, introducing it into an uncolonized stream channel, and letting it circulate until its dissolved oxygen had reached equilibrium with the atmosphere. The slope of a plot of the rate of change of dissolved oxygen against deficit estimated the reaeration coefficient.

Dissolved oxygen and temperature measurements were made with two YSI-57 DO meters, each of which monitored 16 streams. The sensors were placed in the turbulent area where the water entered the upstream end of each channel. Because the calibration of the probes sometimes changed markedly over the course of a day, the dissolved oxygen and temperature readings were recalibrated with Winkler titrations and an accurate mercury thermometer every half hour. The correct calibration for readings between calibrations was determined by linear interpolation on a plot of the calibration vs. time.

Productivity was monitored weekly except at the time of application of the acute treatments; then it was measured the day before, the day of, and three days after herbicide injection. The dissolved oxygen in each stream was monitored every 15 minutes from 0.5 hour before dawn to one hour after sunset, once an hour from then until midnight, and once at the following dawn. Predawn and post-sunset readings estimated respiration, and by assuming a linear transition from the morning to the evening respiratory rate we could correct each time interval's estimate of net community productivity estimates, which could then be summed over the day to summarize photosynthetic performance. However, in some cases more intense respiration during the daylight hours than at night yielded negative gross primary productivity estimates. We have reported these, and have called our estimates apparent gross primary productivity (AGPP). Factorial analysis of variance was used for statistical analysis. Finally, in order to get a general estimate of the persistence of each of the herbicides in the stream water, chemical analysis was performed on frozen water samples.

## RESULTS

Although the artificial streams have heavily colonized with algae by the end of each six-week experiment, they never attained a steady-state species composition. The dominant algae in both years were the diatoms Nitzschia, Rhopalodia and Achnanthes, the green algae Scenedesmus and Cladophora, and the cyanobacteria Chroococcus, Nostoc, Phormidium and Anabaena.

Figs. 1, 2 and 3 and Table 1 show the effects of the acute and chronic treatments on dawn-to-dusk AGPP. In the figures, 1, 2, 3 and 4 represent the mean AGPP for the 0, 0.1, 1 and 10 ppm treatments, respectively, including both chronically exposed and unexposed streams. Treatments spanned by the same vertical bar to the right were not significantly different from each other (Duncan's multiple range test). The letters A-G indicate response a week before (A), a day before (B), the day of (C), three days after (D), and one, two and three weeks after (E, F, G) the application of the acute treatments. MS means the Minter Spring (1981) experiments and LB indicates the Little Brazos (1982) work. We will discuss the results by herbicide.

In terms of productivity, atrazine was the most toxic herbicide tested. Fig. 1 shows that both 10 and 1 ppm caused significant inhibition of AGPP in both years, an inhibition which was more persistent in the case of the Little Brazos algae. Also, the Little Brazos flora was significantly inhibited by 0.1 ppm atrazine, a concentration which did not have a significant effect on the AGPP of the Minter Spring algae. We expected that the chronic treatment of 0.01 ppm atrazine would select for a resistant flora during colonization, but there was no evidence that the chronically exposed streams responded differently to the acute treatments than the non-exposed streams. The only effect of chronic exposure

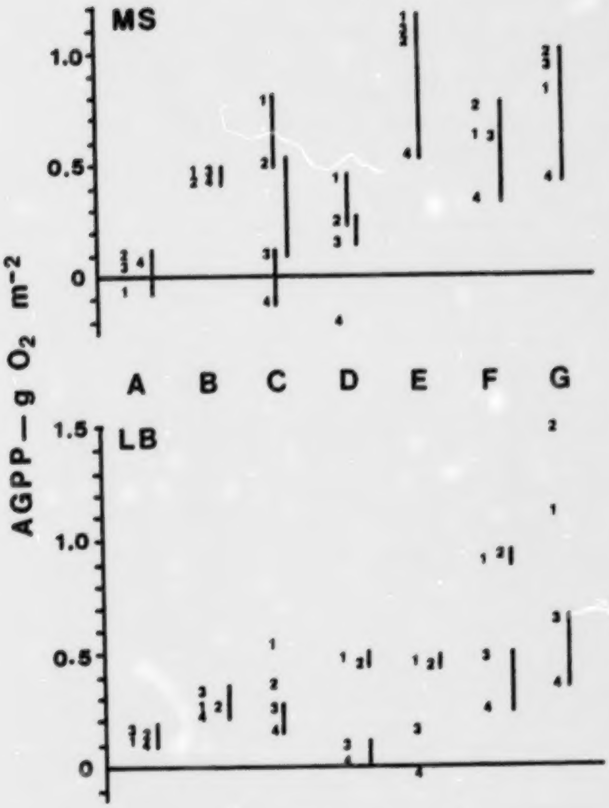

Fig. 1. Response of AGPP to acute treatment in the atrazine experiments.

seemed to be a slight reduction in productivity. While the difference was never great, on seven out of eight occasions in 1981 and in every case in 1983, the chronically exposed streams had a lower AGPP and net community productivity than the non-exposed streams (Table 1). There is less than a 5% chance that this pattern would occur if the productivity of the two treatments was equal.

Trifluralin disappeared very rapidly from the stream water and had no important effects on productivity. Therefore, we have not presented trifluralin results in the figures or Table 1.

MSMA (Fig. 2) at 10 ppm produced a significant reduction in AGPP in both years, but in 1982 this was detectable only by analysis of the change in AGPP from the day before acute treatment to the day of treatment. The Little Brazos community recovered rapidly, with the 10 ppm AGPP exceeding the control AGPP within three days after treatment. By contrast, the AGPP of the 10 ppm Minter Spring streams remained the lowest of the four treatments for at least two weeks after treatment. The 0.1 and 1 ppm treatments and the 0.01 ppm chronic treatment caused no detectable effect on AGPP.

The Little Brazos algae seemed markedly more sensitive to paraquat. The acute paraquat treatments produced no effects on the productivity of the Minter Spring community, but 10 ppm paraquat produced a transient but sharp reduction in the photosynthesis of the Little Brazos community (Fig. 3). Recovery occurred within a week, after which the 10 ppm treatment's productivity exceeded that of the control. The chronic treatments also reflected a greater paraquat sensitivity on the part of the Little Brazos algae. Table 1 shows several significant 1981 paraquat chronic effects, but they lack a consistent pattern. On the other hand, significant chronic effects were entirely lacking in 1982, but the

Table 1. AGPP (mg $O_2$ $m^{-2}$) in the chronic treatments. The 0 ppm and 0.01 ppm treatments are the first and second values in each pair, respectively. One or two asterisks opposite a pair indicate a significant difference between the two values at the 0.05 or 0.01 level. The letters A-G are explained in the text. MS indicates Minter Spring and LB indicates the Little Brazos. Missing values are the result of inclement weather.

| | Atrazine | | MSMA | | Paraquat | |
|---|---|---|---|---|---|---|
| | MS | LB | MS | LB | MS | LB |
| A | 74 | 163** | 382 | 1971 | 155 | 381 |
| | -1 | 90** | 352 | 1725 | 57 | 326 |
| B | 438 | 340** | 483 | 1840 | 137** | 315 |
| | 462 | 220** | 470 | 2126 | 206** | 288 |
| C | 318 | 319 | 341 | 1245 | 188 | 155 |
| | 308 | 314 | 194 | 1449 | 176 | 202 |
| D | 245* | 291 | 249 | 1215 | 26** | 342 |
| | 55* | 223 | 351 | 1547 | 178** | 304 |
| E | 993 | 315* | 591 | 1554 | 187** | 492 |
| | 906 | 187* | 454 | 1703 | 100** | 398 |
| F | 857* | 830* | 891 | 1354 | | 648 |
| | 313* | 467** | 976 | 1518 | | 508 |
| G | 883 | 1116** | | 2048 | 147** | 770 |
| | 698 | 679** | | 2281 | 265** | 678 |

exposed streams had a lower AGPP on every occasion but one. As with atrazine, this highly non-random pattern indicates a slight but detectable inhibitory effect of 0.01 ppm paraquat.

## CONCLUSIONS

While contamination of streams with herbicide runoff is a common problem, the concentration of herbicides detected in river surveys are usually very low. Nevertheless, herbicide concentrations in runoff may be approximately three orders of magnitude greater than in a mixed stream, and algae in the immediate vicinity of a runoff entry point may experience a relatively high herbicide concentration. This investigation attempted to determine whether atrazine, trifluralin, MSMA and paraquat at concentrations of 10 ppm and below could significantly inhibit the productivity of stream algae. We also tried to determine the probable importance of induced resistance to herbicides.

Trifluralin had no effect on productivity. Atrazine's effect was uniformly toxic to algal communities derived from both Minter Spring and the agriculturally-impacted Little Brazos River. Exposure to 10 and 1 ppm significantly reduced photosynthesis in both communities, and 0.1 ppm caused a significant reduction in the

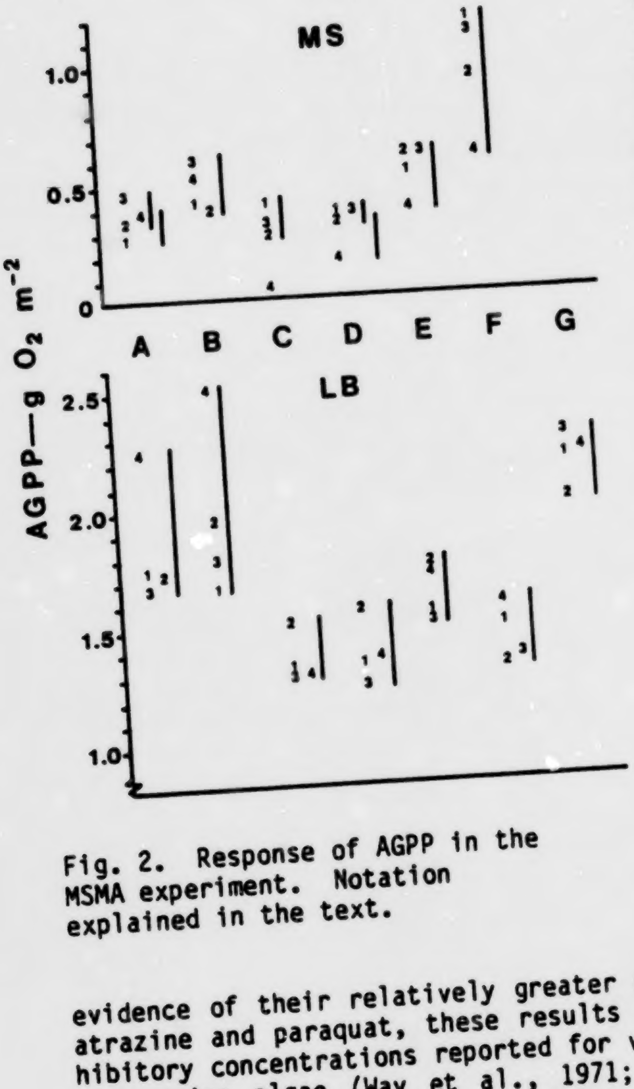

Fig. 2. Response of AGPP in the MSMA experiment. Notation explained in the text.

photosynthesis of the Little Brazos community. The Little Brazos community was also slower to recover from atrazine poisoning. Even the chronic treatment of 0.01 ppm caused a detectable inhibition of photosynthesis in both communities. MSMA had less of a productivity effect than atrazine. Only the 10 ppm concentration had a significant effect, and the Minter Spring community seemed to be more sensitive and recover more slowly. The sensitivities of the two communities diverged most strongly in the paraquat experiments, in which the Minter Spring algae seemed unaffected by 10 ppm but the Little Brazos algae were strongly inhibited for three to seven days. A slight but consistent reduction of the productivity of the Little Brazos algae by the 0.01 ppm chronic treatment also gave evidence of their relatively greater sensitivity to paraquat. For atrazine and paraquat, these results are consistent with the inhibitory concentrations reported for various planktonic freshwater and marine algae (Way et al., 1971; Hollister and Walsh, 1973; Torres and Flaherty, 1976; Butler, 1977; de Noyelles et al., 1982). For MSMA, however, our findings of detectable toxicity at 10 ppm contrast strongly with reports by Richardson et al. (1979) that they could find no effect on the photosynthesis of Chlorella and Euglena of MSMA concentrations of 2490 ppm and 840 ppm. Sensitivity to herbicides varies remarkably between different species and strains of algae--Valentine and Bingham (1976) reported a naturally resistant Euglena strain that could grow in the presence of 10 ppm atrazine, and Torres and O'Flaherty (1976) reported reactions of different Chlorella vulgaris inocula to 1 ppm atrazine that ranged from an 87% inhibition to a 29% increase of chlorophyll development. Our results, however, show that it could be a serious mistake to extrapolate data from single (perhaps resistant) species to predict the response of a whole community.

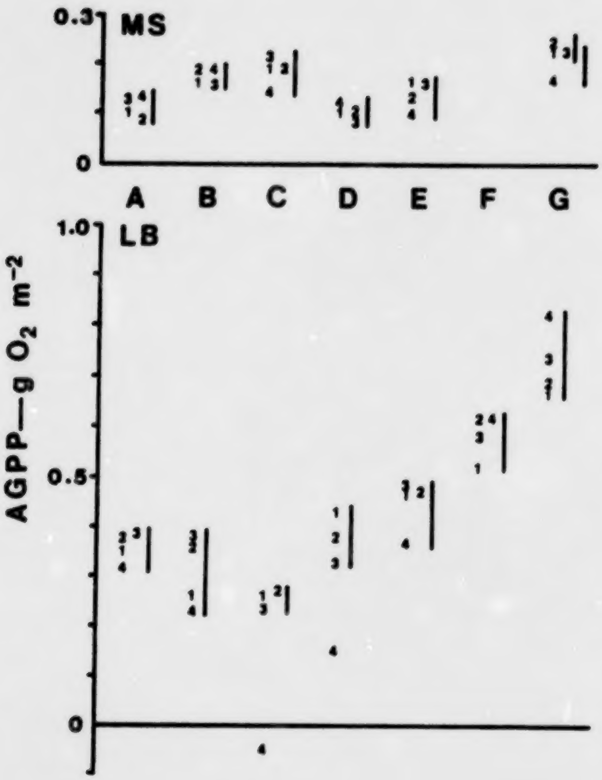

Fig. 3. Response of AGPP in the paraquat experiment. Notation explained in the text.

Surprisingly, we saw little evidence of induced resistance to any herbicides. The Little Brazos algae, which have been subjected to agricultural runoff for many years, seemed more, rather than less, sensitive to atrazine and paraquat than the Minter Spring algae.

The comparison between the two data sets is hindered by the inevitable differences in species composition, weather and water chemistry between the two years. Also, while atrazine, trifluralin, MSMA and paraquat are in use on the Little Brazos watershed, we have no data on the exposure of the river's algae to them. Nevertheless, it is clear that the results do not support the hypothesis of widespread resistance to herbicides by agricultural stream algae. More interpretable data on resistance are provided by the chronic treatments, which showed that three weeks of prior exposure had essentially no effect on the flora's ability to resist any of the herbicides. We are now analyzing data on periphyton species composition that will allow a fuller exploration of the effect of the chronic treatments.

The results show that concentrations of herbicides present in runoff can cause depression of the productivity of an intact periphyton community. The possible deleterious effects of a productivity reduction include increased sloughing of the algal mat, reduction in the productivity of associated grazers such as chironomids and mayfly nymphs, loss of habitat structural complexity, and species shifts (perhaps permanent) as resistant algae rapidly preempt substrates vacated by sensitive species. Because the Little Brazos riffles have thick mats of Cladophora, a severe loss of standing crop might even increase bottom erosion and turbidity. However, the most important effect would probably be the reduction of riffle oxygen evolution, which might cause oxygen stress for the inhabitants of the deep, more pondlike sections of the river.

However, we must emphasize that our experiments used maximum herbicide concentrations approximately one order of magnitude higher than those seen in runoff, and that the herbicide circulated in the streams until it was degraded or removed. Halflives of atrazine, MSMA and paraquat in the water averaged 3.2, 2.3 and 0.5 days, respectively, so that the exposure period for the flora was probably much longer than would be seen in a natural stream, where a heavily contaminated parcel of water would pass a point quickly. We are now preparing an investigation of interaction of concentration and exposure time in atrazine toxicity. A final consideration is that, except in the case of 10 ppm atrazine and 10 ppm paraquat in the Little Brazos experiment, the depression of photosynthesis was incomplete and disappeared in a few days. Dissolved oxygen in the shallow, turbulent streams rarely dropped more than 2 ppm below saturation. Oxygen reductions more severe than this commonly occur in the Little Brazos due to flooding and very cloudy days, and the flora and fauna should be adapted to them.

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# THE NEMATODE BIOASSAY FOR TOXICITY IN BIOLOGICAL SAMPLES OR SEDIMENTS FROM CONTAMINATED AQUATIC ECOSYSTEMS

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## ABSTRACT

An assay using the free-living nematode Panagrellus redivivus is described in detail. The assay permits the determination of lethal, semilethal, developmental, and genotoxic effects. The assay provides a quantitative indication of the net toxic effects of chronic exposure to a specific complex environmental sample, or individual components of a contaminated ecosystem. The assay has been applied to environmental contaminants, chemical fractions of sediments from contaminatd aquatic ecosystems, and samples of biological tissues from contaminated systems. The major source of biotoxicity of sediments from Tobin Lake, on the Saskatchewan River, resides in a neutral fraction. Toxicity was found in brain tissue of large pike, but not small pike, from the Winnipeg River system, probably resulting from residual mercury accumulated by the older fish from the early 1970s. Toxicity was also specifically found in fatty tissue from red suckers at a downstream site, but not in fish from an upstream site, permitting an estimate of the position and type of contamination. In each case, the nematode bioassay provides a cost-effective, rapid indicator of the net biological effect (risk), and the nature of the source of the risk.

## INTRODUCTION

The toxic effects of contaminants to aquatic ecosystems fall into several classes. At one extreme are those effects that result in the death of all or a significant proportion of biological populations exposed to the contaminants. Such lethal effects, although relatively rare, have a high public profile. At the other extreme are those effects that are expressed only after a significant period of time, usually measured in generations, or afflicting only a very small proportion of the exposed biological population at some period of time removed from the initial exposure. Included in this latter group are the high public-profile effects of mutagenesis and carcinogenesis. Between these two extremes are a range of toxic effects, both reversible and irreversible, acting to reduce the overall fitness of the members of biological populations exposed to the contaminants.

To further compound the problem of environmental toxicology, real ecosystems do not have a single contaminating chemical species, but are exposed to a range of potentially toxic materials from both natural sources and as a consequence of human activity. The combined toxic effects of these contaminants may be additive, synergistic, or antagonistic. Furthermore, the target organisms will normally show a dose-dependent adaptive response to the range of contaminating agents.

The conventional approach to environmental toxicology has focused on the chemical characterization of the contaminated ecosystems, to determine the presence of chemicals from a previously established list of toxicants. In this approach, bioassays are utilized for the determination of the dose-dependent toxic effects of individual chemicals or binary mixtures of chemicals. Such tests are utilized to establish either maximal "safe" levels or minimal "risk" levels of individual chemicals. Such levels are normally based on the application of some correction factor to that concentration of the test material that produces some specific level of lethality within a previously determined time, or the concentration producing a significant level of mutagenesis. Such an approach ignores the potential range of toxic effects, adaptive responses, and the potential for toxic interactions between contaminants.

The approach we are advocating is the utilization of biological testing to establish the toxic effects within a contaminated ecosystem, and to further use biological testing as an analytic method for the chemical determination and ranking of the sources of biological risk in the contaminated ecosystems. Much of the chemical logic of this approach has been presented (Samoiloff et al., 1983). Here we would like to present further details of the bioassay system that we have utilized, and to present some demonstrations of the applicability of this approach.

## THE *Panagrellus redivivus* BIOASSAY

The free-living nematode *Panagrellus redivivus* has been shown to be a rapid, cost-effective indicator of lethal, semilethal, developmental, and genotoxic effects (Samoiloff et al., 1980; Samoiloff et al., 1983). The bioassay is performed by exposing a synchronous population of the earliest free-swimming stage (L2) of *P. redivivus* to the tested sample for the 96-hour test period.

During this period, a control population of L2 animals will grow through three molts to the adult stage. At each molt, the organisms sample their environment, and either continue development to the next stage or arrest their growth and development. An increase in the numbers of animals arrested in each of the three molts, relative to the numbers arrested in control populations, provides a quantitative measure of the net biotoxicity of the tested sample. The final (third) molt requires extensive gene activity, and a significant specific arrest of test animals at this stage, relative to a control population, is an indicator of a specific inhibition of normal gene function in animals exposed to the tested material. Lethality and semilethality are determined by recording the size of the tested population during the 96-hour test period.

P. redivivus is a multicellular animal, with a tissue level of organization. At the cellular and biochemical level it is similar to other animals, including man, although there are obvious differences at the physiological level and in the potential pathways of exposure to toxicants. The nematode bioassay is, nevertheless, a reliable simple indicator of biotoxicity.

The P. redivivus bioassay will, upon analysis, generate two distinct values. The first of these, termed fitness is a quantitative indicator of the growth and survival of the test population, relative to appropriate controls. Fitness can range from 100 (growth and survival equal to controls) to 0 (no survival). The second value is a designation of a highly significant ($P<0.005$) specific effect, relative to controls.

## APPLICATION OF THE P. redivivus BIOASSAY

### The "Tobin Lake-Approach"

One application of the nematode bioassay was to determine the major contributors to toxicity sediments of Tobin Lake, Saskatchewan. This lake represents a major sink for contaminants of the entire North Saskatchewan River, and the South Saskatchewan River downstream of the Diefenbaker Dam. This includes contamination from municipalities, agriculture, mining, the petrochemical industry and pulp mills. Eight fractions are prepared from each sediment sample. The sediments are first extracted with 1:1 acetone-hexane, and this extract is partitioned into water, which is re-extracted with dichloromethane to ultimately obtain four neutral fractions (1-4) of decreasing partition coefficient. The aqueous phase was further separated into a basic fraction (5), an acidic fraction (6), and a pH 7 fraction (8). Fraction 7 consisted of a methanol extract of the previously extracted sediment sample. The details of the extraction protocol have been presented by Samoiloff et al., 1983. Each fraction was tested by the P. redivivus bioassay and by the Salmonella typhimurium assay for mutagenesis (Ames et al., 1975). The standard battery of five bacterial tester strains, each with and without activated mammalian extract (S9), were applied to each fraction.

The results from one Tobin Lake sediment sample are shown in Table 1. The fraction (fraction 2) showing the greatest effect in the nematode bioassay was also the most toxic by the bacterial assay. This fraction contains none of the components that would be judged the greatest sources of risk by conventional chemical analyses. For example, pesticides are primarily in fraction 1, which shows no toxicity by either of the bioassay systems.

Fraction 2 was further subdivded by recovering timed fractions from this extract using HPLC. As shown in Table 2, toxicity, as detected by the *P. redivivus* bioassay, was limited to discrete fractions. Four of these subfractions (3, 8, 12, and 20) showed very significant developmental effects, indicating that these subfractions contained those contaminants of the sediments that are the greatest contributors to biotoxicity in this ecosystem. The chemical nature of the components of these fractions is not yet known. Nevertheless, this approach, using a relatively small number of relatively inexpensive bioassays, provides data for further chemical analysis of the real cause of toxicity in a particular system.

## Analysis of Biological Tissues

Two studies of fish from the Winnipeg River system demonstrate the utility of the *P. redivivus* bioassay. In the 1960s and early 1970s, this river was exposed to large levels of mercury, while in the latter 1970s and early 1980s, the levels of mercury were greatly reduced. As a consequence, larger older fish should contain much higher levels of mercury, in those tissues that selectively accumulate mercury, than smaller younger fish. To test this, muscle, fat and brain tissue of large and small pike, *Esox lucius*, were examined by the *P. redivivus* bioassay. These tissues from three large fish (more than 7 kg), were compared to similar tissues from smaller pike (less than 1.2 kg). The results are shown in Table 3. Significant developmental inhibition was observed in animals grown in extracts of brain tissue from larger fish, relative to test populations grown in brain tissues from the smaller fish. As well, two of the larger fish showed genotoxicity of fatty tissue.

The toxicity found associated with brain tissue of the larger pike are what would be predicted on the basis of the history of mercury contamination of the Winnipeg River. The toxicity associated with the fatty tissue, however, was unexpected. To investigate the geographical source of the fat-associated toxicity, tissues from fish physically separated by the Seven Sisters Dam were compared. The reference sample fish were obtained upstream of the Dam, while the "test" population were obtained at sites downstream of the Dam. Brain, muscle and fatty tissue from two species, pike (*Exos lucius*) and red sucker (*Moxostoma macrolepidotum*), were

Table 1. Nematode and bacterial assays of fractions of Tobin Lake sediments.

| Fraction | Nematode Assay Effect | Nematode Assay Fitness | Bacterial Assay +S9 | Bacterial Assay -S9 |
|---|---|---|---|---|
| 1 | - | 91 | 0/5 | 0/5 |
| 2 | D | 50 | 3/5 | 5/5 |
| 3 | - | 83 | 0/5 | 1/5 |
| 4 | - | 94 | 0/5 | 0/5 |
| 5 | G | 87 | 0/5 | 0/5 |
| 6 | - | 87 | 0/5 | 0/5 |
| 7 | - | 100 | 1/5 | 1/5 |
| 8 | D | 69 | 0/5 | 1/5 |

D = significant ($P<0.005$) developmental inhibition

G = significant ($P<0.005$) genotoxic effect

Salmonella assay data presented as number of strains showing a mutagenic or cytotoxic response/ number of tester strains.

Table 2. Toxicity of subfractions of fraction 2.

| Subfraction | Effect | Fitness |
|---|---|---|
| 1 | - | 83 |
| 2 | - | 62 |
| 3 | D | 45 |
| 4 | - | 96 |
| 5 | - | 95 |
| 6 | - | 96 |
| 7 | - | 95 |
| 8 | D | 51 |
| 9 | - | 98 |
| 10 | - | 98 |
| 11 | - | 70 |
| 12 | D | 52 |
| 13 | - | 98 |
| 14 | - | 67 |
| 15 | - | 100 |
| 16 | - | 53 |
| 17 | G | 70 |
| 18 | - | 58 |
| 19 | - | 70 |
| 20 | D | 46 |

Table 3. Toxicity of tissues from pike (*Esox lucius*).

| Fish | Tissue | Effect | Fitness |
|---|---|---|---|
| A | Brain | D | 64 |
| A | Muscle | - | 92 |
| A | Fat | - | 98 |
| B | Brain | D | 45 |
| B | Muscle | - | 89 |
| B | Fat | G | 84 |
| C | Brain | D | 48 |
| C | Muscle | - | 92 |
| C | Fat | G | 83 |

Table 4. Toxicity in pike and red sucker tissues.

The data present effects on downstream fish relative to upstream fish.

| Species | Fish | Tissue | Effect | Fitness |
|---|---|---|---|---|
| pike | A | Brain | - | 97 |
| pike | B | Brain | - | 100 |
| pike | C | Brain | - | 94 |
| sucker | D | Brain | - | 96 |
| sucker | E | Brain | - | 98 |
| sucker | F | Brain | - | 100 |
| pike | A | Muscle | - | 83 |
| pike | B | Muscle | - | 94 |
| pike | C | Muscle | - | 95 |
| sucker | D | Muscle | - | 93 |
| sucker | E | Muscle | - | 85 |
| sucker | F | Muscle | - | 98 |
| pike | A | Fat | G | 66 |
| pike | B | Fat | - | 93 |
| pike | C | Fat | - | 99 |
| sucker | D | Fat | G | 74 |
| sucker | E | Fat | G | 65 |
| sucker | F | Fat | D | 64 |

examined, pairing upstream and downstream fish by sex and size as nearly as possible. Pike between 0.7 and 1.2 kg and suckers between 0.5 and 0.9 kg were examined.

The results of this study are shown in Table 4. Only one of three downstream pike had toxicity in fatty tissue. No toxicity was observed in the muscle or brain tissue of the pike or suckers. Each of the downstream suckers, however, had significant toxicity associated with their fatty tissue, relative to the upstream suckers. The data suggest that there is a source of contaminant downstream from the Seven Sisters Dam, but upstream from Outfall Bay, the site from which the downstream samples were obtained. Since suckers are bottom-feeders, the contaminant, accumulated in fatty tissue is probably associated with sediment or particles in the water column.

## CONCLUSIONS

The nematode bioassay, or similar biological tests, can be used as an analytical methodology to determine the chemicals presenting real sources of toxic risk in contaminated aquatic ecosystems, to determine the presence of tissue specific toxicants, or to locate point sources of such contaminants. Such laboratory-based biological assays are cost-effective, and provide data on toxic materials not available by more conventional methods. While their use in aquatic toxicology has, thus far, been limited to some studies in western Canada by the Environmental Protection Service, this approach, using the nematode bioassay, has been widely applied in studies of indoor air quality. We urge a wider usage of this approach as a supplement to more conventional methods in aquatic toxicology.

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## SESSION II: HYDROLOGY

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# EVALUATION OF THE HYDROMETRIC NETWORK ON THE PEMBINA RIVER THROUGH SIMPLE STATISTICS

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## ABSTRACT

Flow statistics for the Pembina River in Manitoba are reviewed to identify any trends which may assist in the evaluation of the existing hydrometric network. Strong linear relationships were found between the logarithms of drainage basin area and the logarithms of the mean, median, standard deviation and range of the annual mean flows. The same relationships were found to exist but to be less distinct for the annual peak flows. Preliminary conclusions indicate that it may be possible to use these relationships to estimate the mean, median, standard deviation and range of annual mean and annual peak flows for ungauged locations in the river system. The results also suggest that hydrometric networks should be designed to ensure that stream gauging stations are located uniformly across the range of drainage areas within a particular watershed.

## INTRODUCTION

Much of the recent research activity in the design of new and the evaluation of existing hydrometric networks has been based on the more advanced statistical procedures. In many situations, however, the quality and content of the raw data does not justify the use of these advanced and generally quite complex procedures. Furthermore, as the statistical parameters become more complex, their relationships to the physical system they represent may become disguised.

This paper reports on the results of a hydrometric network evaluation that used simple statistics. The use of these simple statistical parameters enables the results of the analyses to be easily related to physical characteristics of the basin being studied, thus minimizing the chance that the essence of the data will be lost in the statistics. It should be noted that the concept of using simple statistical models in place of the more advanced statistical methods has already received some attention for the Canadian Prairies (Stolte, 1980). This study, however, is directed toward the direct use of the simple statistical parameters in the evaluation of an existing hydrometric network.

## DESCRIPTION OF STUDY PLAN

The river chosen for study was the Pembina River which flows through Manitoba and North Dakota (Fig. 1). The data used were taken from Environmental Canada Surface Data records (Environment Canada, 1980). The hydrometric parameters of interest in this study are the discharges of the Pembina River and its tributaries. There are a total of 20 flow gauging stations within the basin (Fig. 2). While the lengths of record range from 10 to 74 years, some of the stations are only seasonal stations generally operating from March through November of each year. The length and period of record at each station and nature (i.e. seasonal or year round) of the station are summarized in Table 1.

Before proceeding with review of the flow statistics, the data for the annual mean flows were analyzed to determine independence and the existence of any trend within the data at every station. Using non-parametric tests, i.e., Spearman rank order correlation coefficient tests (Shiau and Condie, 1980), at the 95% confidence level, no trend or dependence was observed at any station. These results ensured that the data at each station were homogeneous and could therefore be treated as a random series.

## PARAMETERS USED IN THE STUDY

### Annual Mean Flows

The first part of the analysis involved study of the statistics of the annual mean flows at each gauging station. Since some of the stations are maintained on a seasonal basis, it was necessary to interpolate flows for those months for which no flow values were available. This interpolation was performed by assuming a logarithmic flow recession. The logarithmic flow recession was performed in the following manner. If the first recorded monthly mean flow (normally the March flow) of a particular year was zero, or less than the last monthly mean flow (normally the November flow) of the preceding year, the flow was assumed to decrease logarithmically with time between the last recorded flow of one year to the first recorded flow of the following year. If the first recorded flow of a particular year was larger than the last recorded flow of the previous year, the flow was assumed to decrease logarithmically with time from the last recorded flow to zero at mid-February of the next year, and from there to increase logarithmically with time to the first observed flow of the new year. The annual mean flows were then calculated using the 'corrected' data. Since the contribution of the flows in these unrecorded months to the mean annual flows of the whole year are small, any error that exists as a result of the above assumption is very small. For example, at stations 05OA005, 05OB001, and 05OB007 where winter monthly flows are available, use of the assumed distribution in place of the recorded flows resulted in errors in the average annual mean of 5%, 5%, and 4%, respectively. It should be noted that these three stations include two of the most downstream stations and the smallest basin in the system.

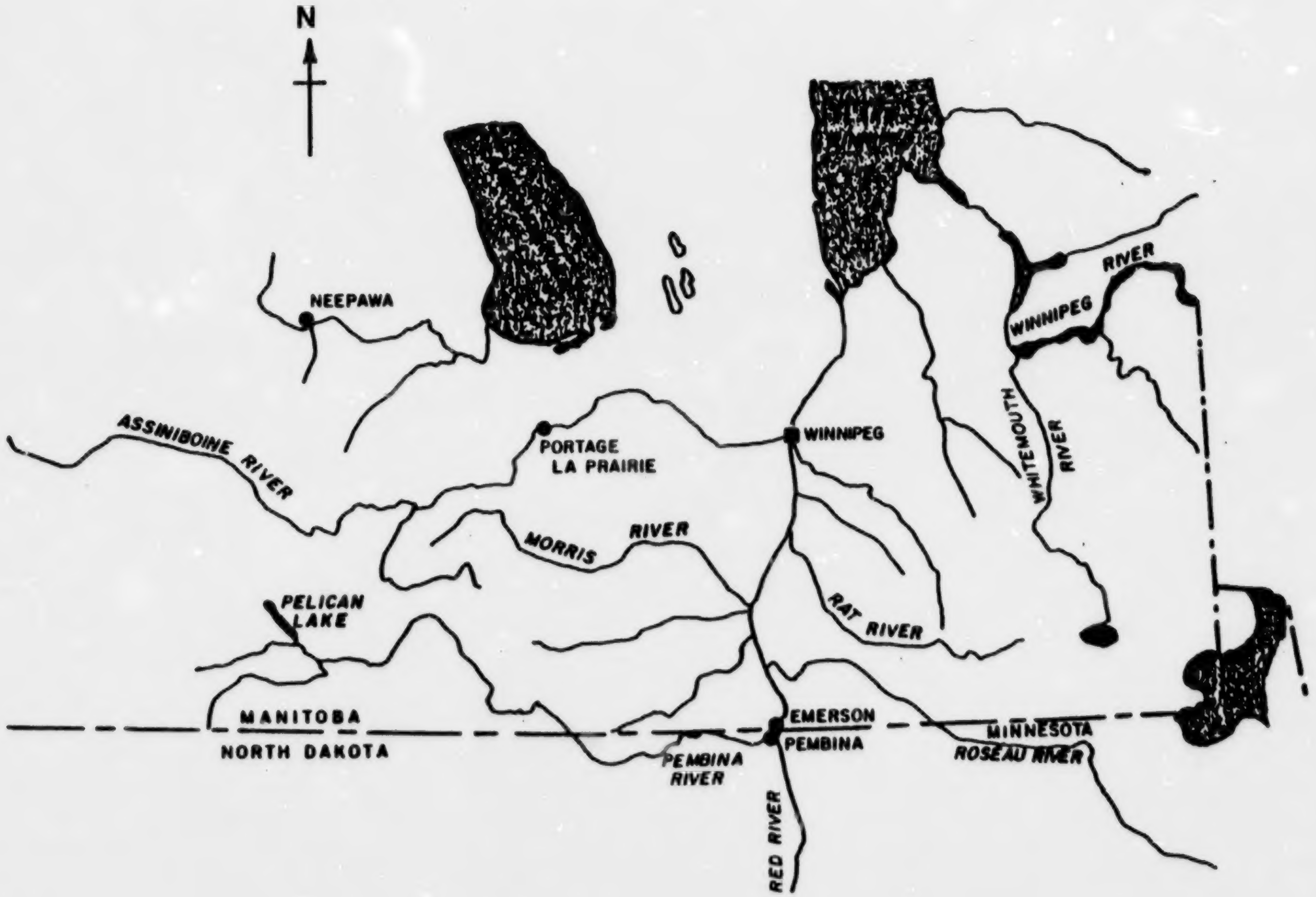

Fig. 1. Location of Pembina River System.

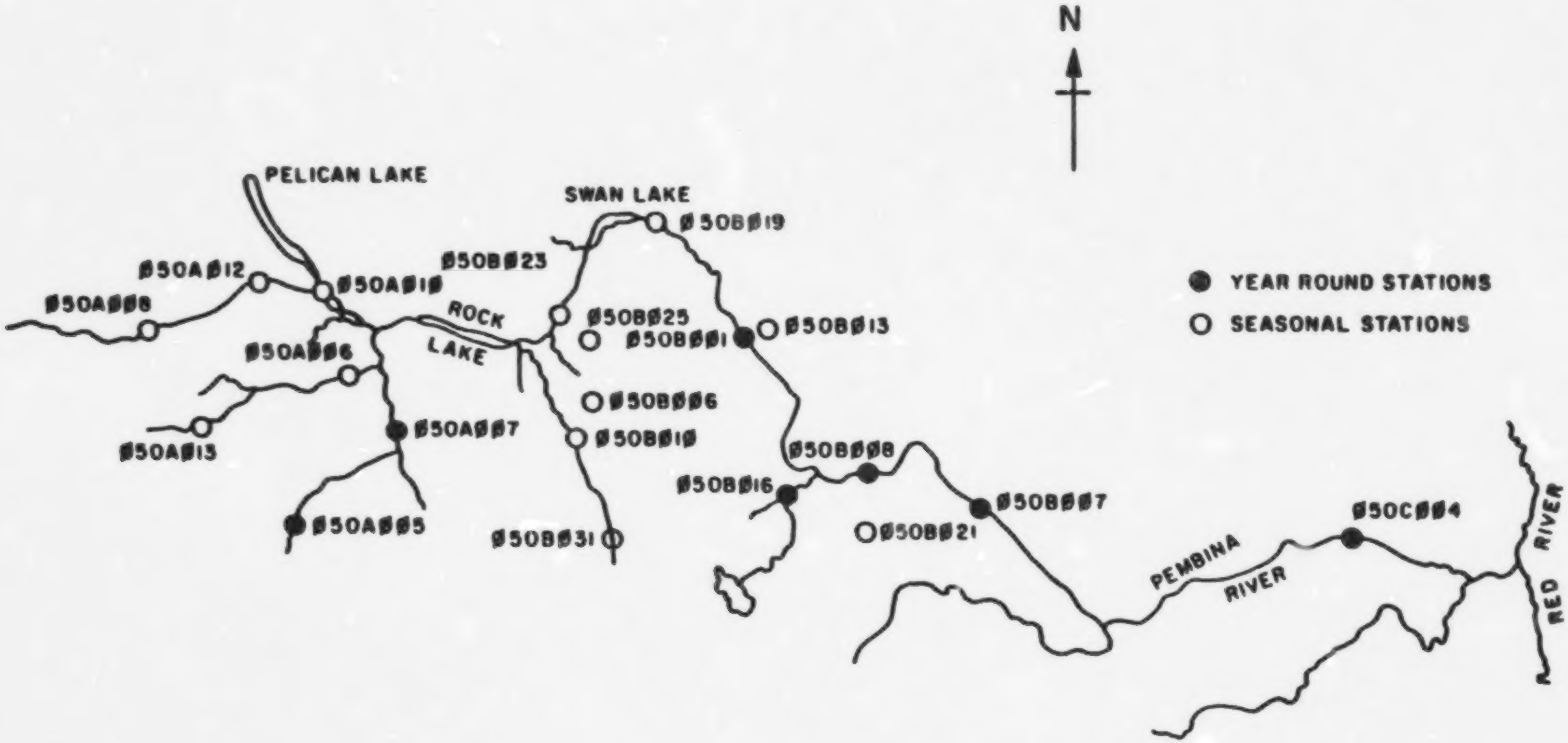

Fig. 2. Location of Stream Gauging Stations on Pembina River System.

Table 1. Summary of Gauging Stations.

| STATION NUMBER | STATION NAME | NO. OF YRS OF RECORD | PERIOD OF RECORD | DRAINAGE AREA (km²) | DRAINAGE AREA (km²) |
|---|---|---|---|---|---|
| 05OC004 | Pembina River near Neche | 73 | 1903-1980[1] | 8470 | 5366 |
| 05OB007 | Pembina River near Windygates | 19 | 1962-1980 | 7510 | 4462 |
| 05OB008 | Pembina River near Kaleida | 13 | 1957-1969 | 7120 | 4172 |
| 05OB001 | Pembina River near La Riviere | 15 | 1963-1977 | 5310 | 3351 |
| 05OB019 | Pembina River near Swan Lake | 10 | 1962-1972(S) | 4970 | 3110 |
| 05OB023 | Pembina River below Crystal Creek | 18 | 1962-1980(S) | 4480 | 2714 |
| 05OA007 | Badger Creek near Cartwright | 10 | 1959-1980 | 1520 | 735 |
| 05OB016 | Snowflake Creek near Snowflake | 20 | 1961-1980 | 979 | 245 |
| 05OA006 | Long River near Holmfield | 22 | 1959-1980(S) | 578 | 489 |
| 05OA010 | Pembina River above Lorne Lake | 19 | 1962-1980(S) | 544 | 360 |
| 05OA012 | Pembina River above diversion | 14 | 1963-1976(S) | 487 | 328 |
| 05OB010 | Cypress Creek near Clearwater | 22 | 1959-1980(S) | 389 | 282 |
| 05OA008 | Pembina River near Killarney | 22 | 1959-1980(S) | 355 | 279 |
| 05OB021 | Mowbray Creek near Mowbray | 19 | 1962-1980(S) | 262 | 168 |
| 05OA013 | Long River near Killarney | 10 | 1967-1976(S) | 209 | 180 |
| 05OB031 | Cypress Creek near Sarles | 19 | 1961-1980 | 184 | 143 |
| 05OB006 | Crystal Creek near Crystal City | 21 | 1959-1980(S) | 153 | 88 |
| 05OB025 | Pilot Creek near Pilot Mound | 18 | 1963-1980(S) | 147 | 102 |
| 05OB013 | Mary Jane Creek at La Riviere | 21 | 1960-1980(S) | 135 | 111 |
| 05OA005 | Hidden Island Coulee near Hansboro | 79 | 1962-1980 | 68.1 | 61.8 |

(S) Seasonal gauging station.

1) Small number of years missing from record.

Several statistics of the annual mean flows were evaluated and plotted against the gross or physical and effective drainage areas associated with each gauging station. The effective drainage areas used in this study followed the effective drainage area defined by the Canadian Federal Agency, the Prairie Farm Rehabilitation Administration. Under this definition the effective drainage area is that drainage area which contributes to the 2.33 year return period runoff event. The effective drainage area was included in the analysis as it represents the 'contributing' area for flows in some of the drier years. It has, therefore, some effect on both the annual mean and annual peak in these dry years. The range of raw statistics of the annual mean flow considered included, the mean, median, standard deviation, coefficient of skew, coefficient of excess and coefficient of variation. A number of composite statistics were then developed. These composite statistics include mean of the annual mean flows divided by the gross and effective drainage areas, maximum annual mean flow divided by mean of the annual mean flows, median annual mean flow divided by mean annual mean flow, maximum annual mean flow divided by minimum annual flow and maximum annual mean flow minus minimum annual mean flow.

Most of the statistics did not display any meaningful trend when plotted against the two types of drainage areas. There was, however, a very strong linear relationship observed between the logarithms of the gross and effective drainage areas and the logarithms of the mean, median, standard deviation and range (i.e. maximum - minimum) of the annual mean flows. These relationships between these statistics and the gross drainage areas are shown in Figs. 3-6. The relationships for the effective area are not shown but they are very similar to those shown in Figs. 3-6 but displayed a little towards the left due to the smaller effective drainage basin size.

The mean, median, standard deviation and range of the annual mean flows were then plotted linearly against the logarithms of the gross and effective drainage areas (Figs. 7-10). Two distinct regions can be identified in each plot. For gross drainage areas less than 1500 sq km (720 sq km for effective drainage areas) there appears to be one linear relationship while for those gross drainage areas greater than 4300 sq km (2600 sq km for effective drainage areas) there appears to be another distinct linear relationship. These plots also indicate the lack of gauging stations for drainage areas lying between the two threshold levels, i.e. where the linear relationships appear to change. The lack of data suggests that in terms of drainage areas the stations are not spread uniformly across the basin. Examination of Fig. 2 also shows a relative lack of stations in the middle to lower reaches of the river system.

Evidence of flow regulation can be seen in the plots of the logarithms of the gross and effective drainage area against the ratio of maximum to minimum annual mean flow. The plot for the gross drainage area is shown in Fig. 11. The plot for the

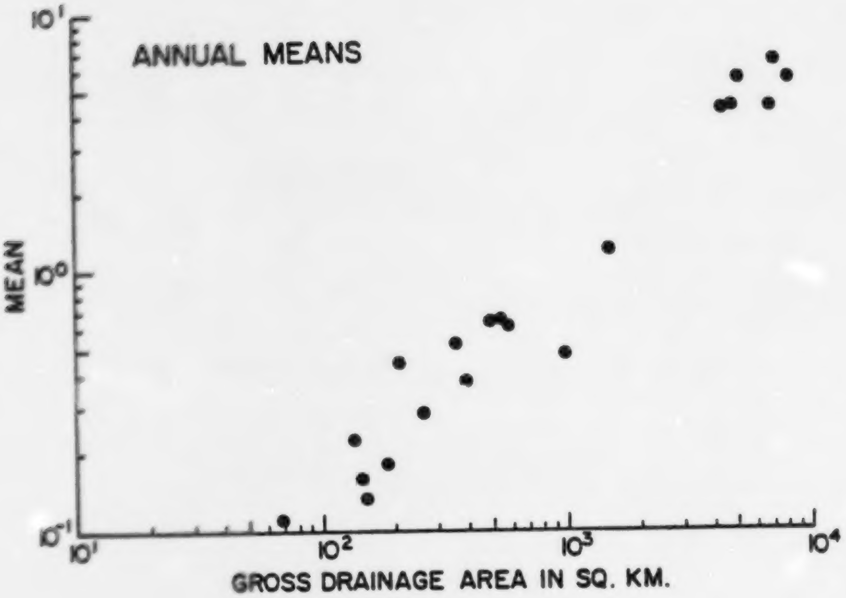

Fig. 3. Plot of mean of annual mean flows against gross drainage areas.

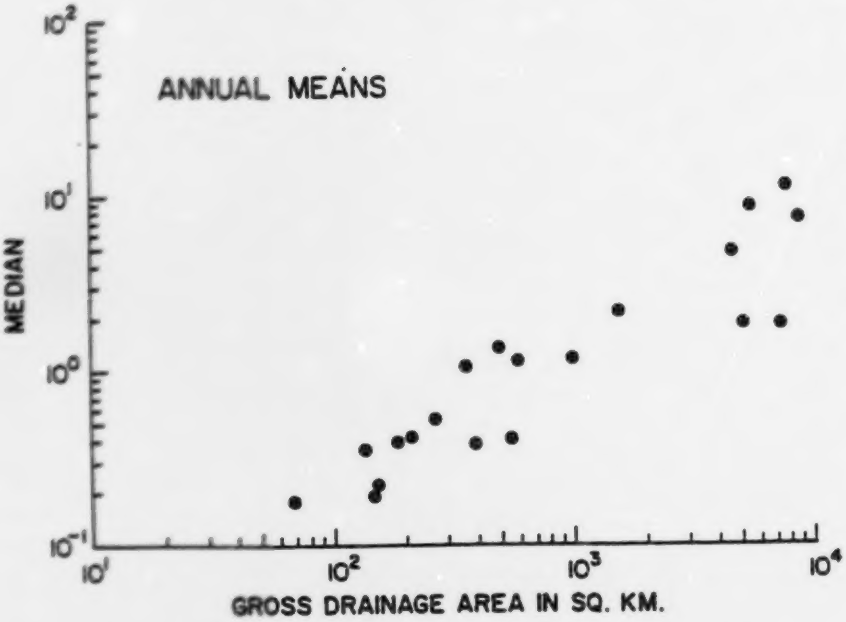

Fig. 4. Plot of median of annual mean flows against gross drainage areas.

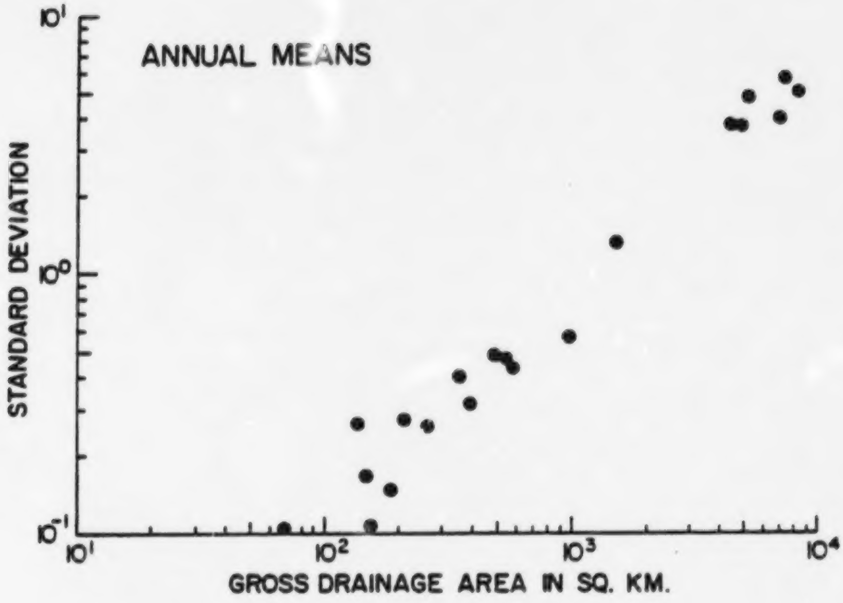

Fig. 5. Plot of standard deviation of annual mean flows against gross drainage areas.

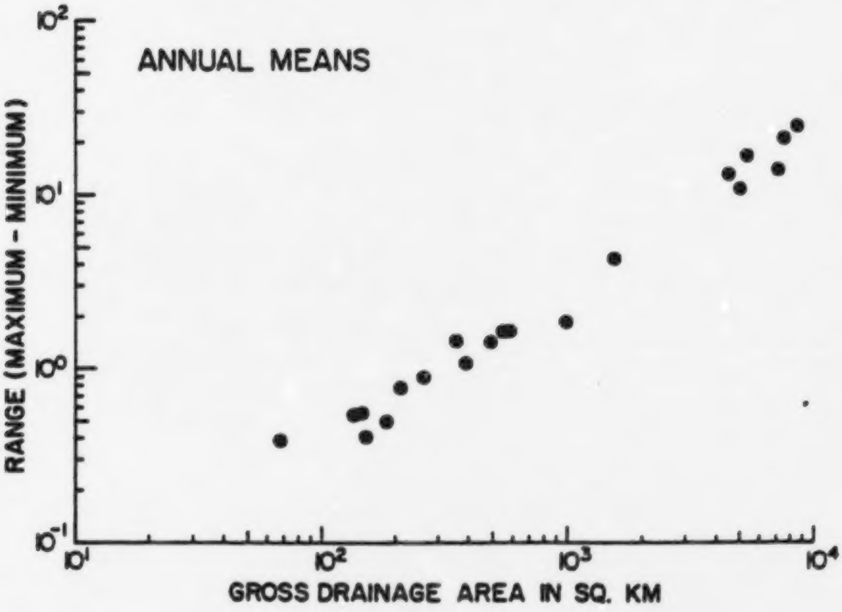

Fig. 6. Plot of range (maximum-minimum) of annual mean flows against gross drainage areas.

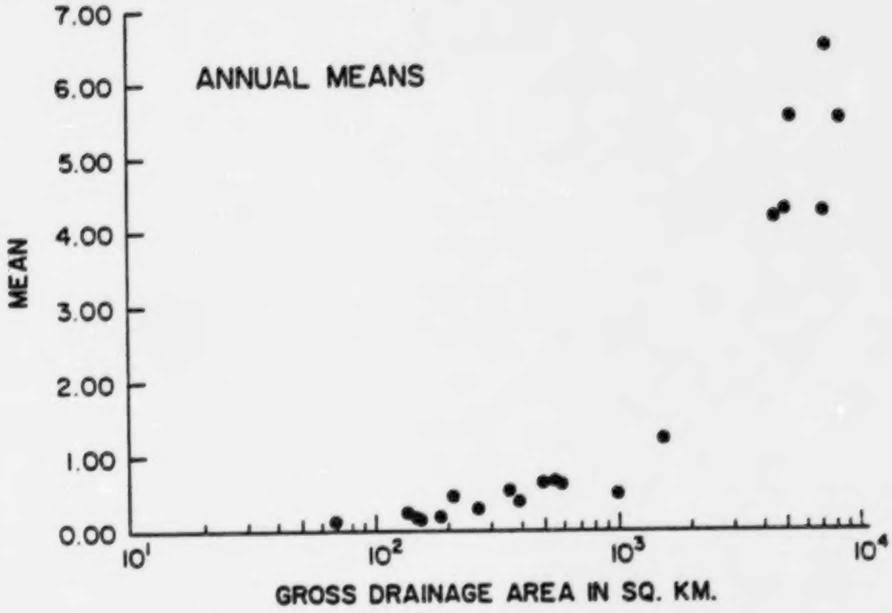

Fig. 7. Linear plot of mean of annual mean flows against the logarithm of gross drainage areas.

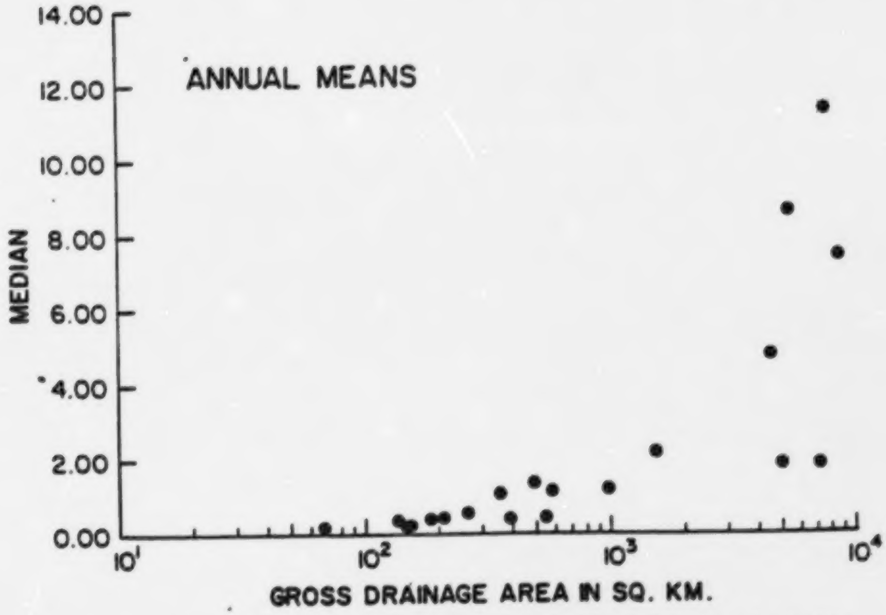

Fig. 8. Linear plot of median of annual mean flows against the logarithm of gross drainage areas.

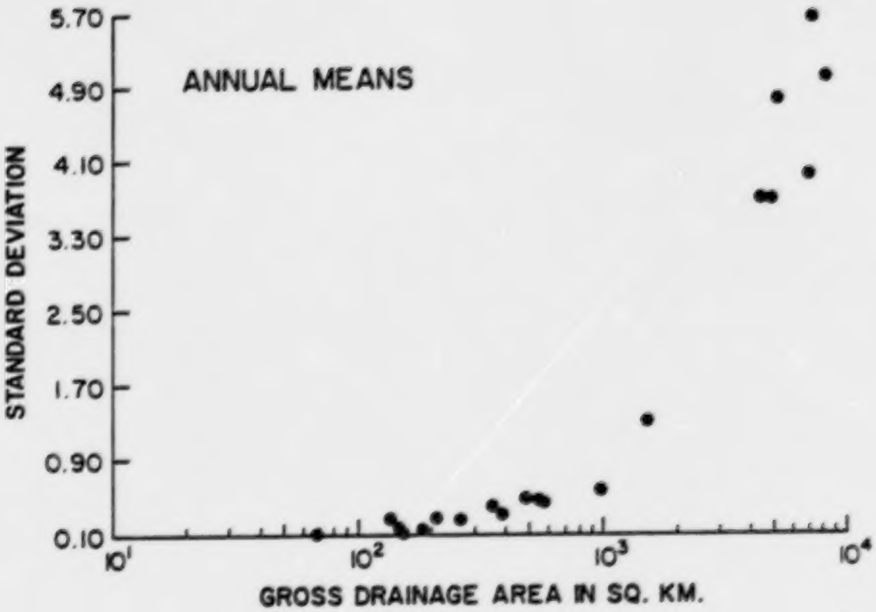

Fig. 9. Linear plot of standard deviation of annual mean flows against the logarithm of gross drainage areas.

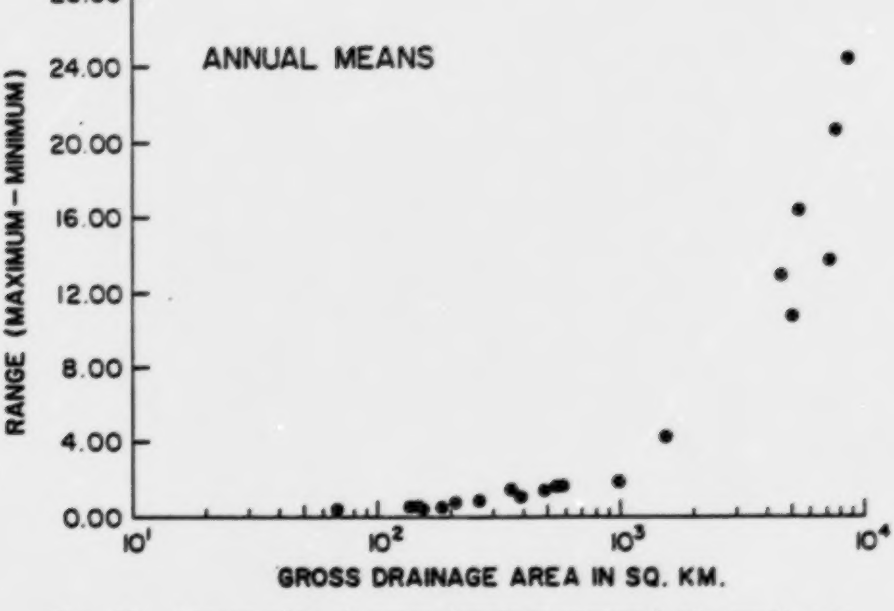

Fig. 10. Linear plot of range (maximum-minimum) of annual mean flows against the logarithm of gross drainage areas.

effective drainage area is very similar and is not given for this reason. Two stations associated with small regulated basins had substantially higher rates than any of the other stations. Since these two basins are relatively small the effects of the other basins rapidly damps out the anomalously high values.

A possible explanation is that while the maximum observed flows pass through the small reservoirs essentially unmodified, the minimum flows are reduced substantially during extended dry periods. This reduction in minimum flow is attributed to the storage of all possible water in the reservoir during low flow periods to make it available for other users. Consequently, as little flow as possible is passed through the reservoir during the dry months. The little flow passing through the reservoir will be that part of the spring runoff which is not needed to bring the reservoir to full storage. The combination of low or zero releases during the dry months and reduced flows during spring runoff cause the annual mean flow to be considerably lower than that occurring under natural conditions, thus increasing the ratio of the maximum to minimum annual mean flow to the levels seen in Fig. 11.

Only one other station had a significant portion of its flow 'regulated.' This station is just below Rock Lake (Station Number 05OB023). As shown in Fig. 11, the ratio for this station is also somewhat larger than the ratios for the 'unregulated' stations. It should be noted that other stations with the Pembina River system are also nominally 'regulated' according to the station identification. However, at these stations the proportion of the flow that is affected by regulation is very small. Consequently, these stations cannot be considered as fully regulated.

The plot of the logarithm of the coefficient of variation against the logarithm of the gross and effective drainage areas indicated that the coefficient of variation is essentially constant across the whole basin with values ranging from around 0.5 to 1.0 (Fig. 12).

## Annual Peak Daily Flows

The same type of analysis was then applied to the annual peak daily flows at each gauging station. Those statistics which showed strong linear relationships for the annual mean flows, i.e. the logarithms of the mean, median, standard deviation and range also showed some relationship for the annual daily peaks. The relationships for the gross drainage are shown in Figs. 13-16. The relationships for the effective drainage are similar to those for the gross drainage areas and are not shown. It can be seen in Figs. 13-16 that the relationships for the annual daily peaks do not appear to be as strong as those for the mean annual flows. The reason for the wider scatter observed for the annual daily peaks is believed to be a function of localized climatic variations across the basin during period of peak flow. The effects of

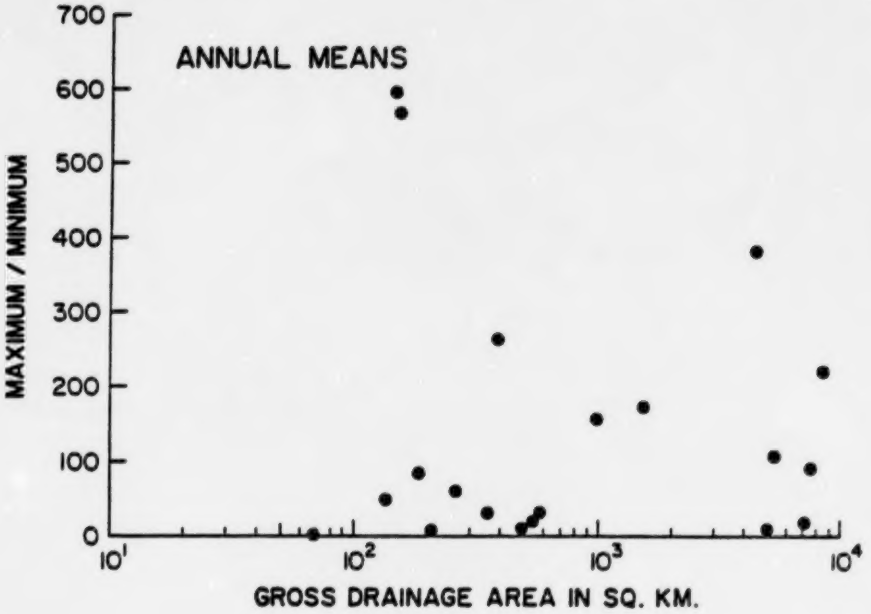

Fig. 11. Plot of ratios of maximum to minimum mean annual flows flows against gross drainage areas.

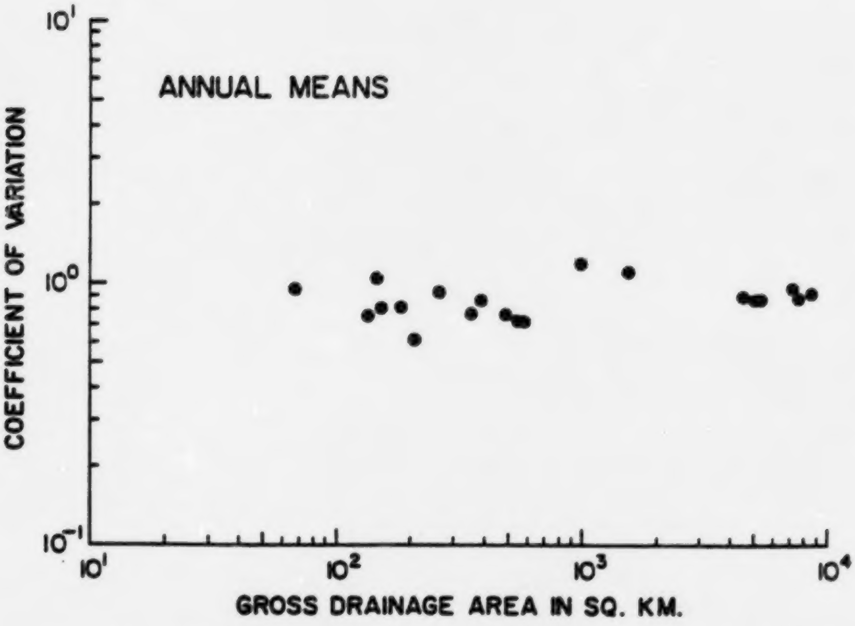

Fig. 12. Plot of coefficient of variation of annual mean flows against gross drainage areas.

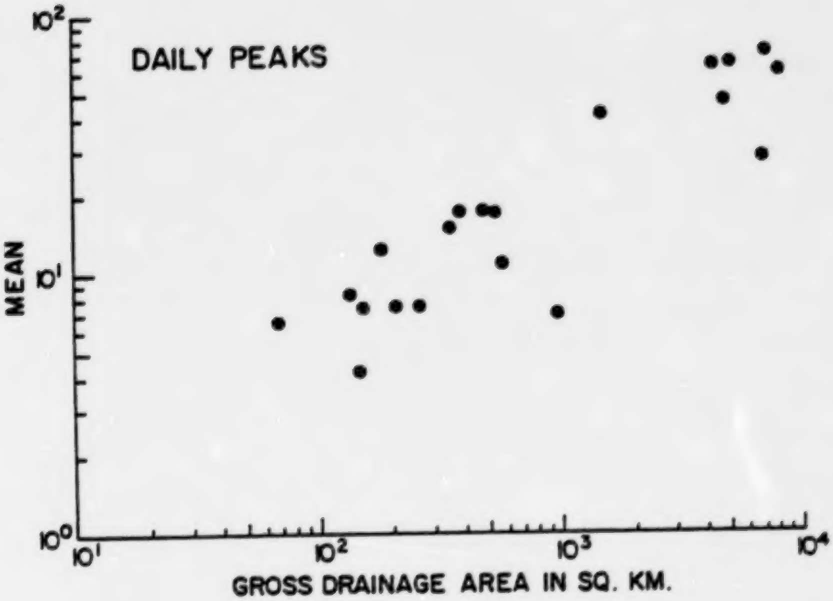

Fig. 13. Plot of mean of annual peak daily flows against gross drainage areas.

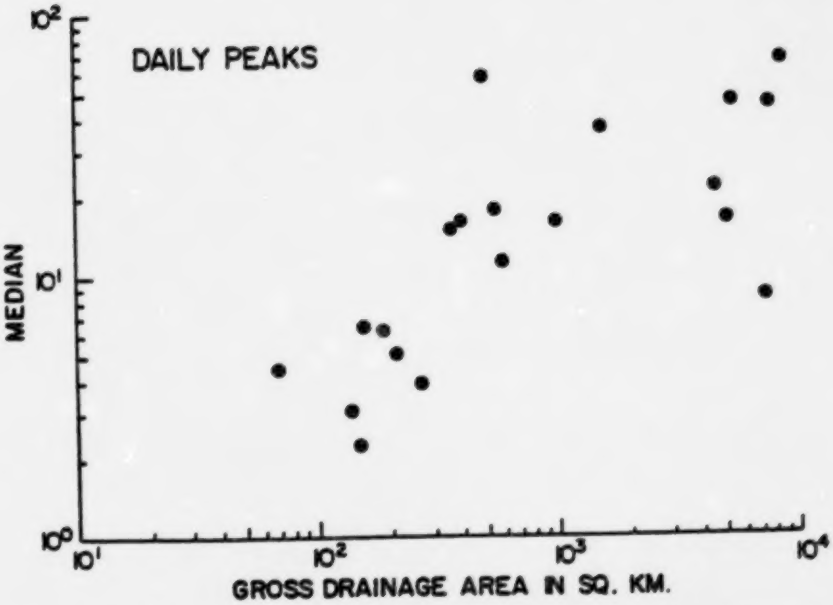

Fig. 14. Plot of median of annual peak daily flows against gross drainage areas.

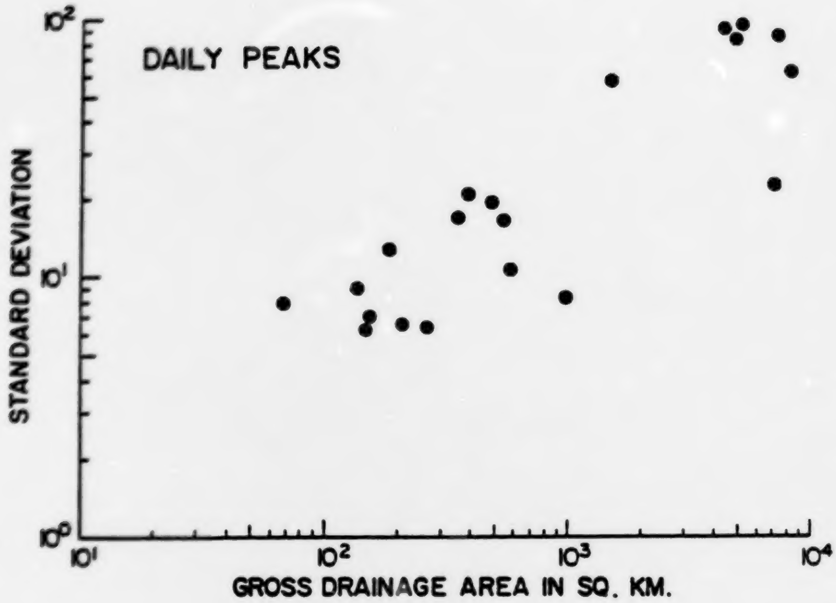

Fig. 15. Plot of standard deviation of annual peak flows against gross drainage areas.

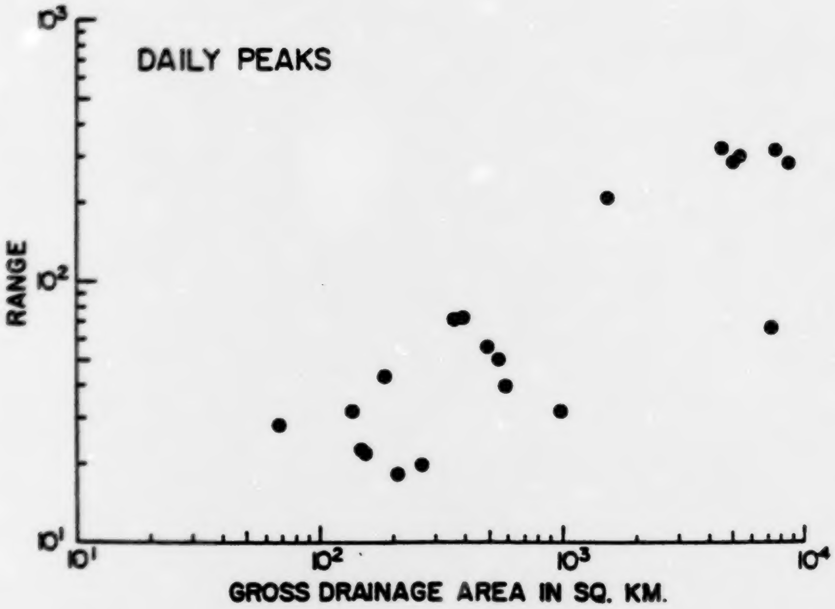

Fig. 16. Plot of range (maximum - minimum) of annual peak daily flows against gross drainage areas.

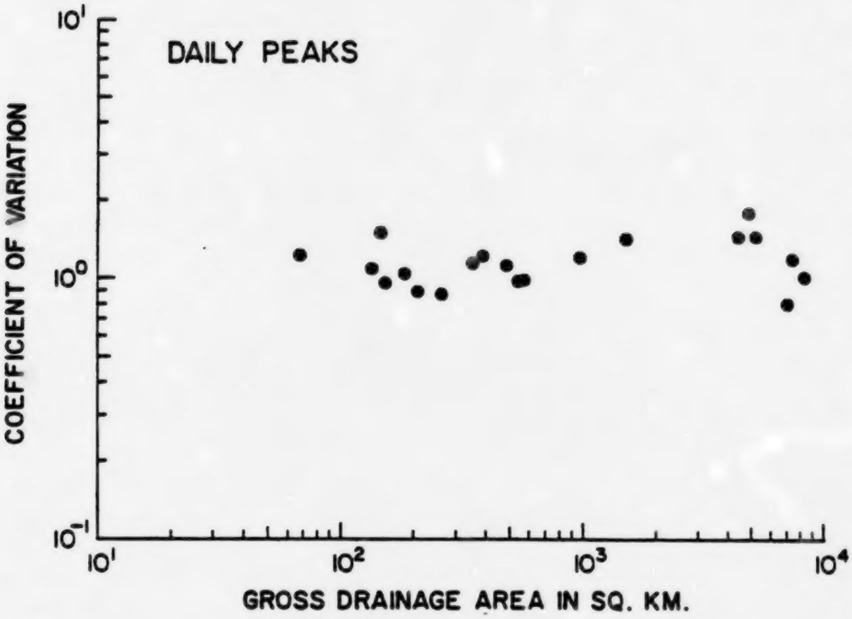

Fig. 17. Plot of coefficient of variation of mean annual daily peak against gross drainage areas.

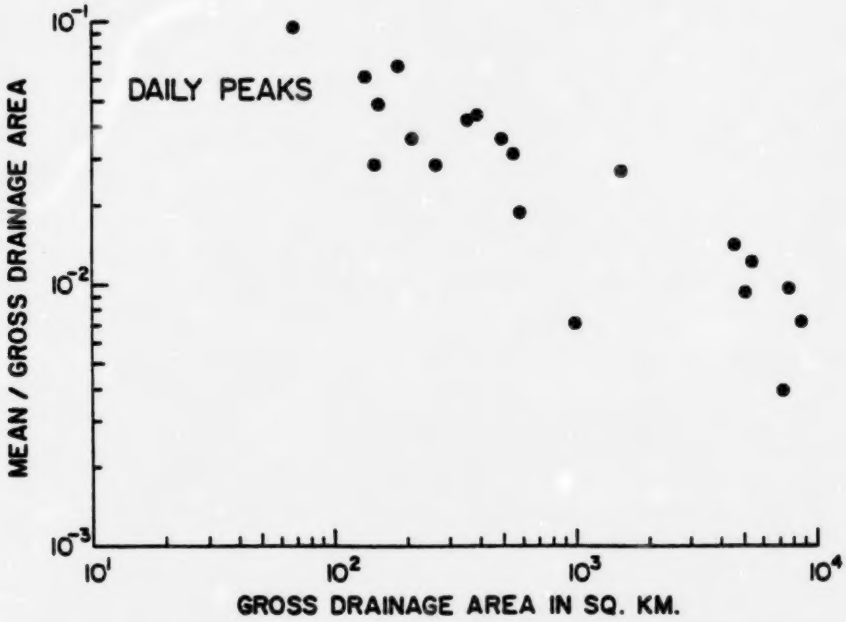

Fig. 18. Plot of ratios of mean annual daily peak to gross drainage area against gross drainage areas.

these local variations would tend to be damped out when the flow is taken over the whole year, i.e. by considering annual mean flows or even flows over a month.

The regulated basins, which were easily identified in the plot of the ratio of maximum to minimum mean annual flows, were not evident in similar plots for the annual daily peaks. The reason for the lack of evidence of the regulated basins in these plots lies in the explanation suggested for their presence in the plots for the annual means. It was suggested that the peak flows would remain essentially unmodified in passages through regulation 'reservoirs.' Since the minimum and maximum daily peaks both refer to peak flow in a particular year, neither would be modified by the regulation in these small basins. Consequently, the regulated basins will be indistinguishable from unregulated basins for annual daily peak flows.

As with the annual mean flows, the coefficient of variation did not show any general trend with either gross or effective drainage area. All values of this coefficient lay between 0.8 and 1.8 (Fig. 17). The wider range in the coefficient of variation for the daily peak flows relative to the annual peaks lies in effect of localized climatic variations at the time of peak flow, as described in the previous paragraph.

One new statistic of the peak daily flows did, however, show a relationship that was not apparent in the plots for the annual mean flows. The plot of the logarithm of the ratio of mean annual daily peak flow to the gross drainage against the logarithms of the gross and effective drainage areas showed a general linear relationship. The relationship for the gross drainage (Fig. 18), shows that a decrease in this ratio can be expected with an increase in the respective drainage areas. It is believed that the decrease in this ratio can be attributed to the separation in time of the peak daily flows in the tributaries and main channel of the river. This temporal separation prevents the peak flows in the tributaries from being directly additive in the main channel, thus reducing this ratio relative to the ratios in the smaller tributaries and in the upstream reaches of the river.

## GENERAL COMMENTS

The above discussions have identified statistics for which relationships have been observed. If these are the statistics of the data required from the hydrometric network, then a more sparse network can be used as long as there are enough stations to identify the general form of the relationship.

The results of this study support earlier work in this field. Dunne and Leopold (1978) reported on the relationship between drainage area and average discharge for four different regions in the United States. One of the regions included Montana, Wyoming, North Dakota and South Dakota. The geography/

hydrology of the study area is similar to the semi-arid conditions in these states. While considerable scatter was apparent in Dunne and Leopold's data the general trend is the same as that found in this study. The reduced scatter observed in this study may be attributed to the fact that all stations analysed lay in the same watershed.

Besides the specific relationships discussed above, a general observation on network design was also identified. It appears that it is very desirable to have a network of hydrometric stations which cover, in a relatively uniform fashion, the range of drainage areas in the basin. For the network on the Pembina River, for example, there are no gauging stations for gross drainage areas between 1500 and 4300 sq km (720 to 2600 sq km for effective drainage areas). The absence of these stations leaves a range of basin sizes for which interpolation must be used. For the Pembina basin, these drainage areas cover the range where the linear plots of the mean, median, standard deviation and range of the mean annual flows against the logarithm of the respective drainage areas show an apparent change from one linear relationship to another. The presence of data for these intermediate drainage basin sizes would clarify conditions considerably. While this statement may appear self obvious, it is quite often overlooked in the setting up of a new network or reduction/improvement of an existing network.

## CONCLUSIONS

While some strong relationships between some data statistics and drainage basin size have been identified, verification of these results on other prairie watersheds is necessary before any general conclusions regarding hydrometric network design can be drawn. This study does, however, identify parameters and statistics which bear further investigation.

## ACKNOWLEDGMENTS

Dale Kimmett and Ian McLaurin of Environment Canada provided the guidance and direction for this study. The research was supported in part by the Natural Sciences and Engineering Research Council in the form of a graduate fellowship to the second author.

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# SEDIMENTOLOGY AND PALEOHYDROLOGY OF WALDSEA LAKE, SASKATCHEWAN

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## ABSTRACT

Waldsea Lake is a small meromictic saline lake in central Saskatchewan. The chemocline was first measured at 4 m depth in 1971, and has since dropped to 9 m. Despite its change in elevation, it is still capable of supporting a bacterial plate composed primarily of Chlorobium spp. Major ion chemistry shows that the lake is of the Mg-Na-$SO_4$-Cl type. The lake irregularly allows massive precipitation of carbonates in the form of aragonite and also occasionally gypsum. These events are rather shortlived, and are represented in the sediment as laminations of nearly pure aragonite of gypsum. Because the lake occupies a closed basin the lacustrine fill provides a detailed record of the late Holocene history of the lake. Sediment cores of the upper 4 m show a complex history of clastic, chemical, and organic sediment input. Superposed on this is an intricate assemblage of early diagenetic effects. The allogenic component consists of fine-grained quartz, dolomite, calcite, feldspars, and clays. Endogenic components include aragonite and gypsum. Early diagenetic dolomite, gypsum, and pyrite are also present. Organic content varies significantly but irregularly throughout the cores. Radiocarbon dating suggests that the upper 4 meters of sediment were deposited during the last 4000 years, and that sedimentation rates have varied significantly. Stratigraphically, these sediments indicate a small shallow, hypersaline lake with extensive mudflats existed in the basin about 4000 years B.P. With the exception of several small reversals, the lake has been continually deepening and becoming less saline throughout its history, likely due to the effects of a moderating climate.

## INTRODUCTION

Saline and hypersaline lakes are a common occurrence in the Great Plains of western Canada and the northern United States. Usually occupying closed drainage basins, these lakes range in size from small prairie potholes to several of the largest inland saline bodies in North America. By virtue of the closed nature of the basins, these lakes respond dramatically to environmental changes and thus their sediment records provide excellent documentation of such changes.

Waldsea Lake is a small, relatively shallow saline lake in central Saskatchewan. It has been known to be meromictic since 1971 (Hammer et al., 1978), and has been the subject of numerous biologically-oriented studies during the past decade. Despite its salinity (25 g/l mixolimnion, 68 g/l monimolimnion), Waldsea Lake is part of a regional park and recreation area. The objectives of this report are to: (a) discuss the modern sedimentology of Waldsea Lake; (b) describe the late Holocene stratigraphic record within the basin; and (c) interpret the fluctuations in various sediment parameters with regard to the paleohydrology and geochemistry of the lake.

## SETTING

Waldsea Lake is located in the northern Great Plains of western Canada about 100 km east of Saskatoon, Saskatchewan (Fig. 1). The area experiences a cold continental climate with a mean January daily temperature of -20°C and a mean July temperature of 18°C. Annual precipitation at Humboldt, about 10 km south of the lake, averages 375 mm per year. Approximately twice this (750 mm) can be lost through evaporation from the lake's surface (CNC/IHD, 1978).

The area is characterized by hummocky to gently rolling topography with generally poorly integrated drainage and ubiquitous closed depressions. The surficial sediment of the region consists of 100-150 m of till with interbedded fluvial and lacustrine gravels, sands, silts, and clays. The bedrock of the area consists of about 1500 m of Phanerozoic sedimentary rocks overlying Precambrian granitic basement. The bedrock surface in the vicinity of Waldsea Lake shows considerable relief caused by glacial and post-glacial erosion (Meneley, 1967). A major bedrock channel, the Hatfield Valley, with relief of up to 100 m, runs north and east of Waldsea Lake.

The lake has a surface area of just under 5 km$^2$ with a natural drainage basin area of 32 km$^2$. An extensive farmland drainage system has increased the watershed area to about 47 km$^2$. Most of the drainage basin is used for agricultural purposes with cultivation extending to the edge of the lake on all sides.

Waldsea Lake has a mean depth of 5.8 m and a maximum depth of 14.5 m (Fig. 2). The shoreline is generally smooth (shoreline development of 1.3) and there are no islands or peninsulas in the basin. The morphometric characteristics of the lake are summarized in Table 1.

Though the hydrologic budget of Waldsea Lake is poorly known, it is estimated that the basin receives 2.5x106 m$^3$ of inflow

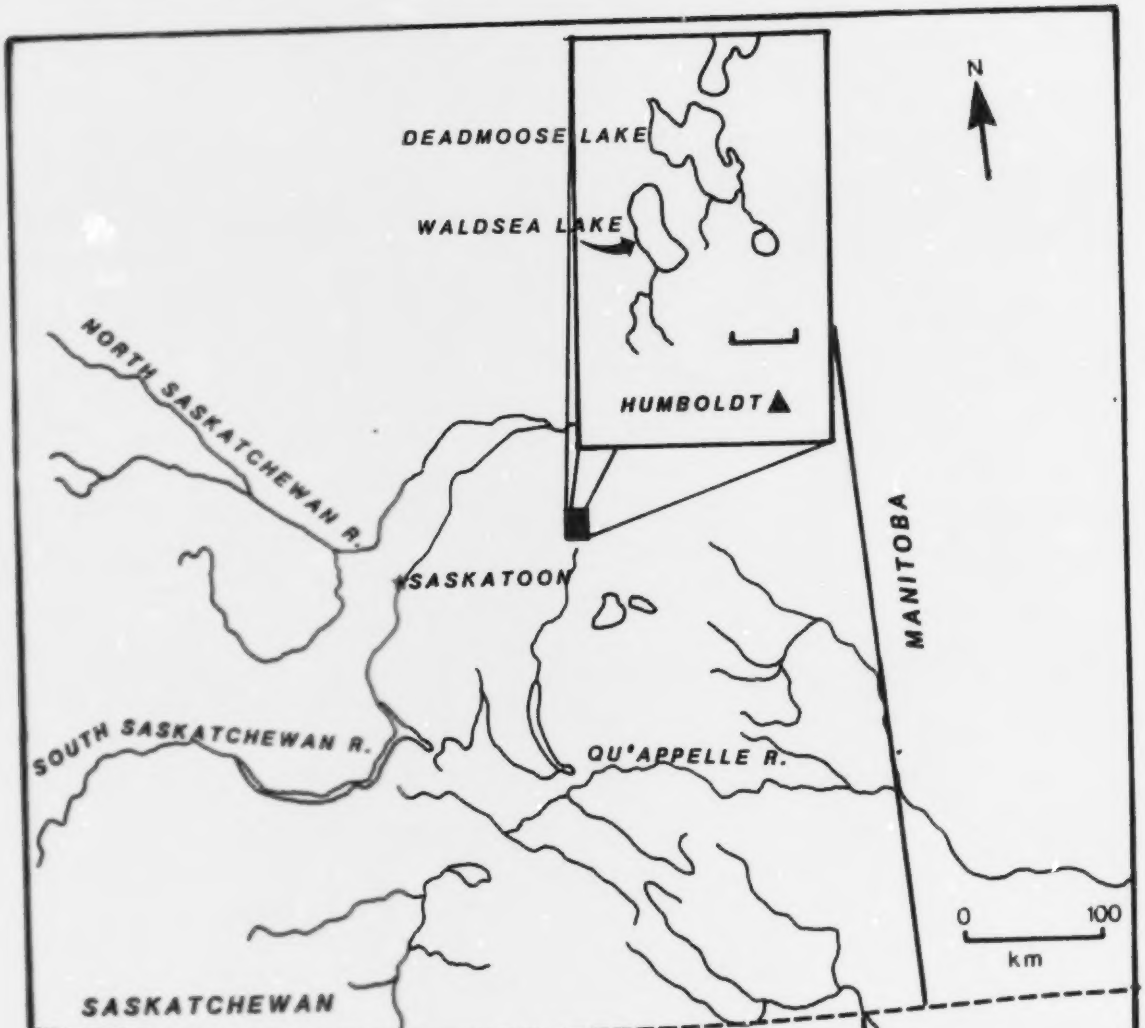

Fig. 1. Location map of Waldsea Lake area. Scale bar on inset equals 2 km.

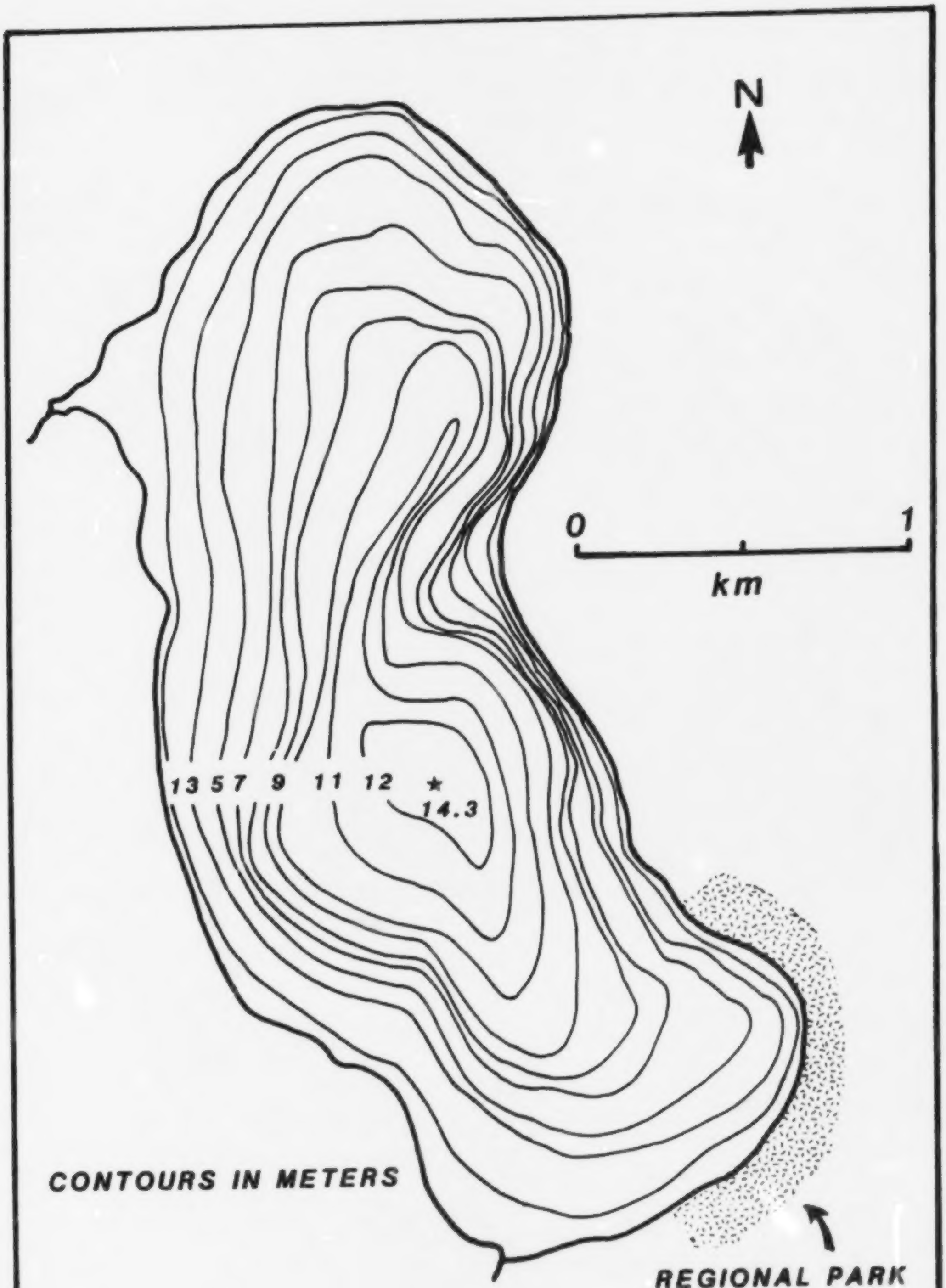

Fig. 2. Bathymetric map of Waldsea Lake (after Swanson, 1978).

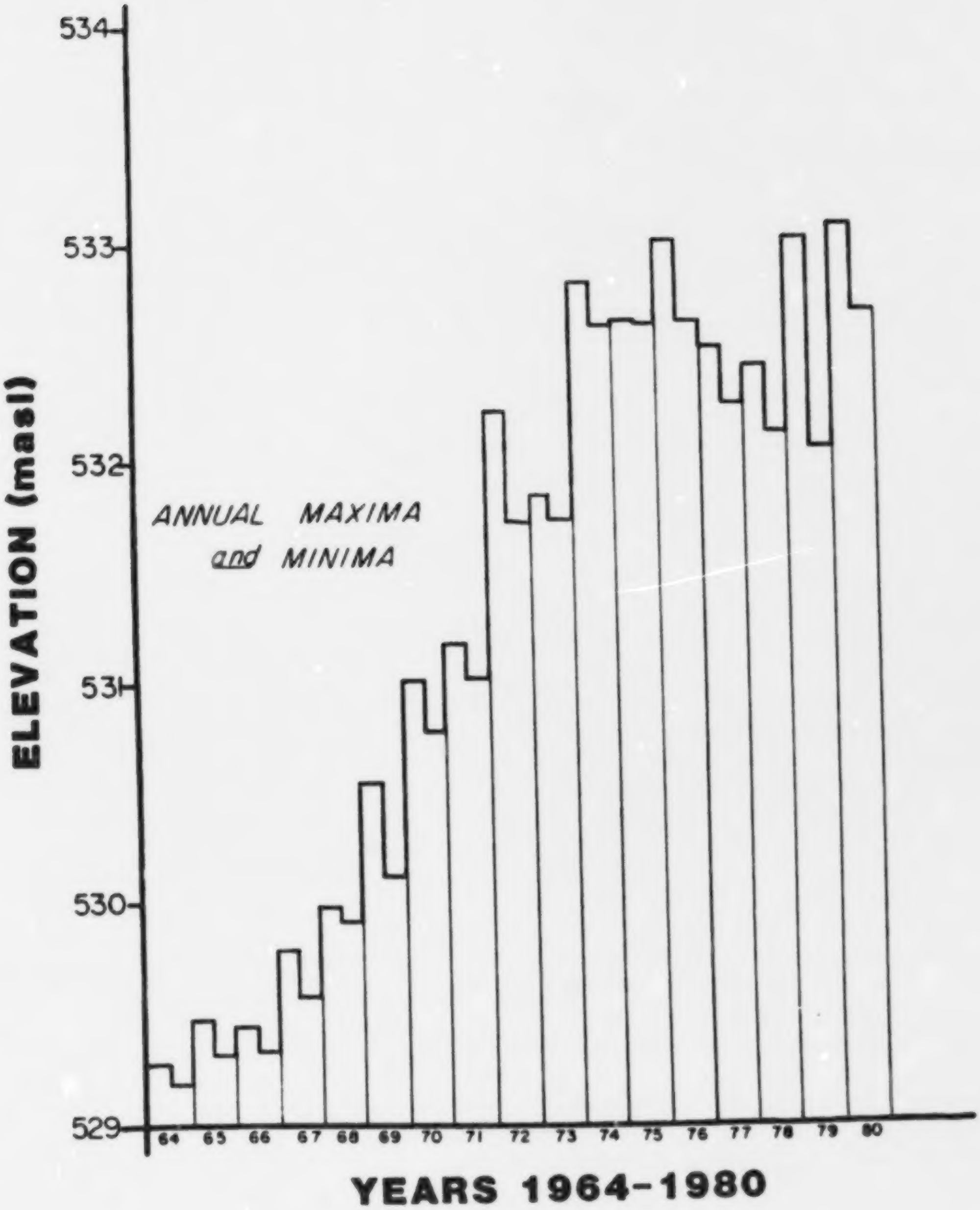

Fig. 3. Changes in surface elevation of Waldsea Lake since 1964.

annually via direct precipitation on the lake's surface and stream runoff. Approximately 3.5x10$^6$ m$^3$ leaves the lake through evaporation. By difference, the groundwater contribution to the basin must be about 1x10$^6$ m$^3$. The water level of Waldsea Lake has risen considerably during the past two decades (Fig. 3). This rise is likely due to an increase in the groundwater component of the hydrologic budget as there is only a very poor correlation ($r=0.176$) with precipitation changes.

Table 1. Selected morphometric parameters for Waldsea Lake

| | |
|---|---|
| Surface area | 4.64 km$^2$ |
| Maximum depth | 14.5 m |
| Mean depth | 5.8 m |
| Shoreline length | 10.7 km |
| Shoreline development | 1.30 |
| Volume | 37.69x10$^6$ m$^3$ |
| Volume development | 1.70 |
| Drainage basin area | 47 km$^2$ |
| Drainage area/lake area | 10.0 |
| Relative depth | 0.63% |
| Maximum effective fetch | 2.2 km |
| Percent volume in mixolimnion | 88.06 |
| Percent volume in monimolimnion | 11.94 |
| Stability of stratification | graphically 4260 g cm/cm$^2$ |
| (Idso, 1973) | mathematically 3797 g cm/cm$^2$ |
| Total dissolved salt | 6.93x10$^8$ kg |
| Percent of total salt in mixolimnion | 80.08 |
| Percent of total salt in monimolimnion | 19.91 |

Waldsea Lake is currently meromictic with the chemocline present at 9 m depth. A bacterial plate of about 30 cm thickness composed of green sulfur bacteria (mainly *Chlorobium* spp.) is located at the chemocline (Lawrence et al., 1978). The meromixis of Waldsea is primarily ectogenic in nature, with man-made drainage diversions and deliberate alteration of the peripheral vegetation having created conditions which are favourable to funneling freshwater runoff into the lake. This increased runoff has resulted in doubling Waldsea's volume in the last two decades. Though there is little actual water chemistry data from before 1971, an initial high salinity, and a rapid increase in volume with only a small increase in surface area, created a relatively stable meromixis. Since the early 1970s, though, the level of the chemocline has dropped 5 m, suggesting that the meromixis is not permanent and that with normal weather conditions and no further major drainage basin disruptions, Waldsea Lake will eventually revert to its previous dimictic state.

## METHODS

Sediment cores and dredge samples were taken in order to study the present-day geochemical/sedimentological regime of Waldsea Lake, the developmental history of the basin, and any possible man-induced changes in the lake. The cores were retrieved using a modified Livingstone corer. Grab samples of the upper 10 cm of sediment were acquired using an Eckman-style dredge. Water samples were taken using a 2 L acrylic Kemmerer water bottle. Sediment pore water was squeezed from the cores using a Wildco pore water extractor.

The cores were analyzed for water content, organic content, and total carbonate content by weight loss on ignition (Dean, 1974). Bulk mineralogy and detailed carbonate mineralogy were semiquantitatively assessed by X-ray diffraction using the methods of Chung (1974a,b) and Goldsmith and Graf (1958). Texture, sedimentary structures, and colour (Munsell) were described from the fresh sediment cores. Trace element content of the cores was done by emission spectroscopy. All water samples were analyzed for major ions by standard laboratory techniques (Stainton et al., 1977).

## WATER CHEMISTRY

Major ion data for Waldsea Lake are shown in Table 2. The chemistry of the mixolimnial water varies moderately from year to year as runoff increases or decreases. Monimolimnial water chemistry remains relatively constant. Even though Waldsea Lake water is perennially slightly supersaturated with respect to various carbonate phases, massive inorganic precipitation of carbonates due to evaporative concentration occurs endogenically on an irregular basis. The elevated Mg/Ca ratio (30-35) and high salinity of the water dictate that aragonite is the carbonate phase which will be precipitated (Muller et al., 1972). Analysis of the water chemistry data using the computer program WATSPEC (Wigley, 1977) indicates that the lake is also near supersaturation with respect to gypsum (log(IAP/Ksp) > 1).

Table 2. Average major ion chemistry of Waldsea Lake (Data from Lawrence, 1978).

| Parameter | Mixolimnion | Monimolimnion |
|---|---|---|
| | ppm | ppm |
| Sodium | 4100 | 7800 |
| Magnesium | 3350 | 6050 |
| Calcium | 106 | 177 |
| Potassium | 300 | 575 |
| Chloride | 4750 | 8650 |
| Sulfate | 16000 | 30000 |
| Bicarbonate | 122 | 122 |
| Silica | 0.3 | 30 |
| pH | 8.4 | 7.7 |
| Eh | +10mv | -200mv |
| Specific conductance mmhos per centimeter | 28.9 | 45.7 |

## MODERN SEDIMENTOLOGY

The modern sediments of Waldsea Lake are mainly sapropelic silty clay and clayey silt in the offshore region of the basin, grading to slightly coarser sediments nearshore. The present-day shoreline deposits consist of a thin mantle of sand and gravel over till and Holocene soil. Due to the significant increase in the level of the lake over the past two decades, the beaches have not yet achieved an equilibrium profile, but rather consist of a wave-cut notch developed into glacial or early Holocene sediment.

Despite Waldsea's salinity and meromixis, physical sedimentation in the lake is very similar to what one might expect from any stratified freshwater lake of similar morphometry (see, for example, Sly, 1977). In Waldsea Lake winnowing of fine-grained material at the shoreline by wave action during transgression of the shoreline is likely a major source of sediment transported to the deeper basin, and may be responsible for accelerated sedimentation rates over the past 20 years. However, wind action is also capable of moving large volumes of allogenic sediment long distances on the Plains. Some of this wind-blown sediment inevitably falls into the bottom deposits. On the basis of our observations over the past two years, this aeolian material may be a very important component of Waldsea's modern sediment budget and efforts to quantify the relative contribution of each of the major allogenic sources are in progress.

In addition to the allogenic component, which is composed of quartz, feldspars, dolomite, calcite, and clay materials, about half of Waldsea's offshore bottom sediment consists of materials generated from processes occurring within the water column (endogenic). This fraction is made up of organic debris, aragonite, and gypsum. As outlined above, the endogenic mineral phases are the result of inorganic precipitation caused by supersaturated conditions.

## STRATIGRAPHY

The upper 4 m of lacustrine fill in the Waldsea Lake basin consists mainly of organic-rich, well-laminated silty clay and clayey silt. Moisture content decreases from about 80% in the youngest sediment to 35% at the base of the cores. Organic matter content ranges from 5-45% but does not exhibit any specific trend with depth. Thin zones of relatively pure organic fibre mats occur within the lower 2 m of section. Sediment colours are generally dark grey (2.5Y2.5/1) to dark greenish grey (5Y2.5/2) with abundant lighter laminae (10YR4/1) throughout.

We divided Waldsea Lake sediments into five major stratigraphic units on the basis of texture, mineralogy, bedding characteristics, colour, and organic content. Each unit likely represents a major change in the water level, chemistry, and trophic state of the lake. The lowermost unit (Unit 1) is a black silty mud with plant fibre mats and mirabilite crystals. Overlying Unit 1 is Unit 2, which is a grey to green gypsum-rich (gypsite) silt containing calcite-coated twigs and algal fibres. Unit 3 is a dark brown to black sapropel with abundant aragonite laminae. Overlying this are Unit 4 (similar to Unit 2) and Unit 5 (similar to Unit 3).

Unit 1, the oldest unit recovered, is a black silty mud with numerous unidentified plant fibre remains and sparse but recognizable Artemia spp. oogonia. The plant fibres occur both as individual fibres and as interwoven mats, some of which contain preserved pigments. Within this sediment are mirabilite ($Na_2SO_4.10\ H_2O$) crystals which are commonly transparent and mud-free and show syntaxial overgrowths and gas-phase fluid inclusions. Vugs the size of the mirabilite crystals are also found in parts of Unit 1. These likely represent mirabilite crystals which have been removed by dissolution and transported by diffusion into the lake water. The mirabilite crystals may not be original primary sediment, but rather may possibly represent intrasedimentary displacive growth by "freezeout" precipitation during the cooler months. In either case, the presence of mirabilite indicated hypersaline conditions with the lake basin at the time of deposition, and probably a much lower lake level.

Units 2 and 4 are quite similar to each other, but each varies greatly in texture and composition on a small scale. Both rounded, silt-sized clastic gypsum laminae and lensoid gypsum plates and rosettes occur within several mm of each other in the section. The rounded gypsum silt is interpreted as primary gypsum undergoing dissolution, whereas the lensoid gypsum is a product of very early diagenesis. The carbonates within these units show even more eclectic textures and structures. These range from finely crystalline buff (10YR5/1) dolomite "hardgrounds" and cemented laminae to calcite-coated twigs and fine algal filaments. In addition these units commonly contain intraclasts of carbonate material that probably were partially consolidated and then ripped up and redeposited by storm-derived currents or waves. The very fine grained aragonite laminae which are characteristic of Units 3 and 5 are rare.

The predominant minerals in Units 2 and 4 are disseminated aragonite, gypsum, dolomite, and quartz. Some of the dolomite is actually a cation-disordered form of the mineral termed protodolomite and, as such, is either a primary precipitate or, more likely, a penecontemporaneous alteration product of pre-existing calcium carbonate. Although the genesis of this domomite in Waldsea Lake has not yet been fully resolved, both formative modes, that is, endogenic and authigenic, imply an elevated $Mg^{2+}/Ca^{2+}$ ratio of the brine and possibly schizohaline conditions.

Unit 2 may be time-correlative with Unit 1, as Unit 1 occurs in the southern part of the lake, and Unit 2 has only been identified to the north. The key to understanding the conditions under which this could occur is by the paleomorphometry of the lake.

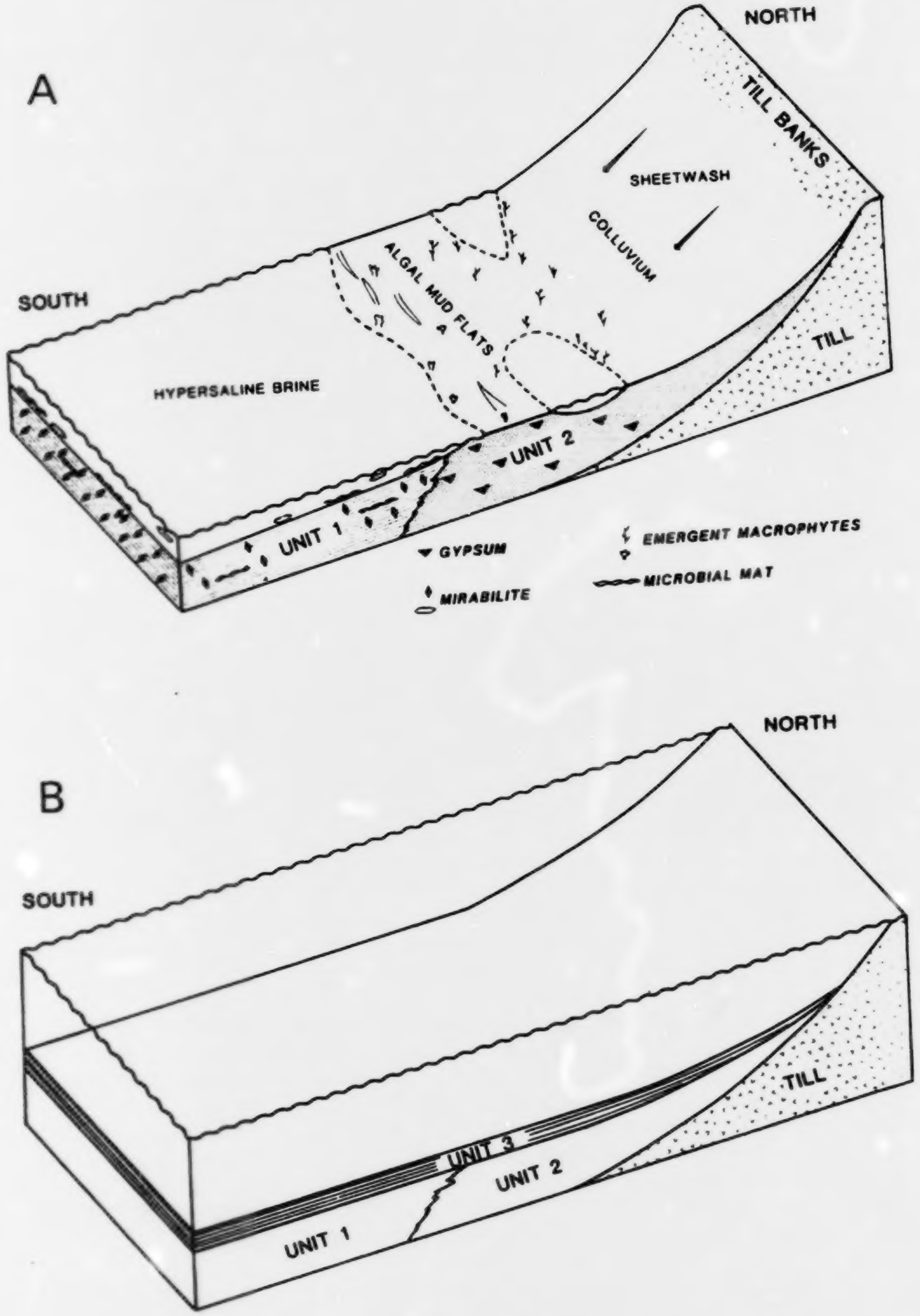

Fig. 4. Schematic block diagram representing the interpreted environmental setting of Waldsea Lake during deposition of Units 1, 2, and 3. A is about 4000 years B.P.; B is about 3000 years B.P.

Fig. 4 shows the interpreted palemorphometry in relation to the cross section of the sediments recovered from Units 1, 2, and 3.

Units 3 and 5 consist exclusively of dark brown to black silty aragonite-rich sapropel to silty sapropelic mud with irregularly spaced very fine-grained aragonite laminae. The colour of these laminae range from white (7.5YR8/8) to buff (10YR5/1) but some show a distinct red (5R5/6) colouration. This latter colour is attributed to organic pigments, such as carotenoids and chlorophylls, sedimented with or either immediately before or after the aragonite precipitaton. Because the aragonite occurs mainly in distinct and relatively pure laminae, it is likely that each lamina was deposited during a "whiting" event. These events may have been produced by high levels of supersaturation brought about by evaporation or accelerated biological uptake of carbon dioxide during photosynthesis. In view of the limited biota due to the salinity of the lake system, the former mechanism seems more plausible.

Aragonite also exists in a disseminated form in Units 3 and 5, indicating that the water column has remained at least slightly supersaturated during relatively long periods of time. Radiocarbon dating of the sediment at the base of Unit 5 yielded an age of 2340+70 years (Beta-6507). The uniformity and thickness of this unit and its similarity to Unit 3 indicates that chemical and hydrologic conditions did not change significantly during long periods of time.

Based on the nature of the lacustrine fill in the Waldsea Lake basin and on the fluctuations in the parameters evaluated, a late Holocene developmental history of the lake can be deduced (Fig. 5). Approximately 4000 years ago a small hypersaline lake existed in the southern portion of the Waldsea Lake basin. Hypersaline mudflats produced laminated carbonate and gypsum sediments (Unit 2) to the north, probably at the same time as the organic and salt-rich mud of Unit 1 was being deposited to the south. Increased runoff and decreased evaporation due to gradual climatic change allowed the expansion and deepening of the lake and deposition of Unit 3. A minor climatic reversal returned evaporative conditions to the basin with possible contraction of the lake and deposition of the gypsum/carbonate rich sediment of Unit 4. This evaporite phase was short-lived, however, and the lake continued to deepen after about 2300 years B.P. Unit 5, with its irregularly spaced aragonite laminae in a mud matrix, suggests relatively constant "deep" water clastic sedimentation conditions, punctuated by frequent massive carbonate precipitation from the water column.

Despite striking evidence of man's activities and manipulations of Waldsea Lake and its catchment area during the past half-century, there seems to be little evidence of significant anthropogenic impact within the sedimentary record. Our preliminary chemical analyses of the heavy metal content of the sediment (including Cd, Cr, Co, Cu, Fe, Pb, Hg, Ni, Ti, V, and Zn) has failed to identify any type of enrichment above background levels in the

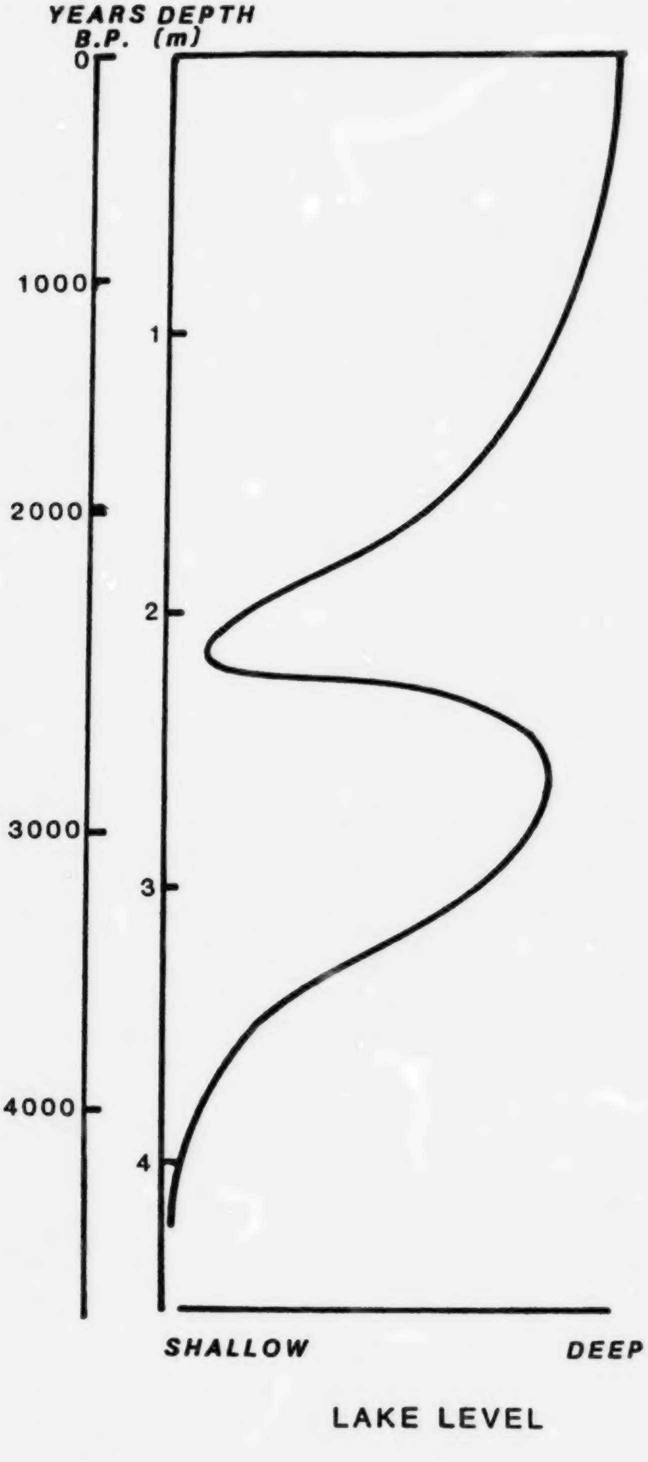

Fig. 5. Generalized lake level history of Waldsea Lake during the last 4500 years.

most recent deposits. Although our dating and chronology of the upper sections of lacustrine fill is not yet complete, there is no obvious change in sediment character or distribution in the top several decimeters, suggesting relatively little actual disruption (in terms of quantity and type of sediment) associated with agricultural development. While it is likely that man's actions have contributed directly to the generation and maintenance of meromixis in the lake over the past two decades, this meromixis is relatively unstable. Continued mixing within the mixolimnion will soon lower the chemocline to the lake bottom and Waldsea Lake will revert to its previous dimictic state.

## CONCLUSIONS

Geolimnological studies on Waldsea Lake are at present in an exciting stage. Because the lake has been saline to hypersaline thoughout most of its last 4000 years, bioturbation is almost completely lacking. Thus, the sediment fill records an extremely detailed history of changes in chemical, vegetational, and hydrologic, as well as diagenetic conditions within and around the basin. Although variations in these environmental conditions are all intimately interdependent, the driving mechanism for maintenance or change in the type and rate of sedimentation is climate. An understanding of the way in which Waldsea Lake, as a sedimentological as well as biological system, responds to given hydrologic and chemical conditions, will make it possible to derive useful information on the temporal pattern of past climatic changes.

Our initial work on the late Holocene record in the lake has indicated that the relative proportions of endogenic and allogenic materials are not constant, and probably fluctuate in response to increased or decreased runoff. From the section of sediments retrieved and studied to date, physical and mineralogical parameters indicate that the lake was at a much lower phase approximately 4500-4000 years ago, and that with only one important reversal at about 3000 years B.P., lake level has been rising nearly continuously for the last 2300 years. This is likely coupled with an overall decrease in salinity, even though small amounts of solid salts of mirabilite are being dissolved out of the sediment and entering the lake by diffusion.

Our most pressing task in the immediate future is to gain a better understanding of the precise mechanisms controlling early diagenesis of the inorganic components in the sediments, particularly those involving the various carbonate and sulfate mineral phases. Once we have a clearer picture of the nature of these diagenetic reactions, a sedimentological-geochemical model for Waldsea Lake can be constructed, and then used to help predict the way in which closed lakes such as this respond to changes in level, chemistry, and other man-induced modifications.

## ACKNOWLEDGMENTS

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# GROUNDWATER COMPONENT OF THE SOUTH SASKATCHEWAN RIVER BASIN IN ALBERTA

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## ABSTRACT

The Planning Division of Alberta Environment requested the Earth Sciences Division to calculate the natural throughflow of groundwater in the South Saskatchewan River Basin, identify the recharge areas, comment on the effects of irrigation on groundwater flow and briefly describe groundwater chemistry and use.

The South Saskatchewan River Basin is the southwestern portion of the Saskatchewan-Nelson River Drainage System and occupies southern Alberta and a small area of Saskatchewan. The area of interest lies almost entirely within Alberta and covers approximately 110,000 $km^2$ (43,000 $mi^2$).

The basin (Fig. 1) can be divided into four physiographic units: the Rocky Mountains that occupy the westernmost area of the basin, the west-central Foothills, the Western Alberta Plains and Porcupine Hills, and the Alberta Plains, which occupy the eastern half of the basin. A remnant plateau, the Cypress Hills, rises in southeastern Alberta.

The basin is divided into four sub-basins: the Oldman, the Bow, the South Saskatchewan River below the confluence of the Oldman and Bow Rivers, and the Red Deer River basin. The Oldman River basin is roughly circular in outline. Most of its headwaters originate in the Rocky Mountains east of the Continental Divide. The Bow River basin has a long narrow trunk that broadens with the branching of headwaters which originate in the Rocky Mountains. The Red Deer River basin is large and rectangular in shape. Most of its tributaries rise in the Western Alberta Plains, with some in the Foothills and Rocky Mountains, as well as north of the river in the Alberta Plains. The area of the headwaters is relatively small and does not border on the Continental Divide. The South Saskatchewan River sub-basin occupies the southeastern region around Medicine Hat. Contained within this sub-basin are several small inland basins such as Many-Island Lake, north of the Cypress Hills, and Forty Mile, Chin, and Etzikom Coulees and Pakowki Lake, all located between Lethbridge and the Cypress Hills.

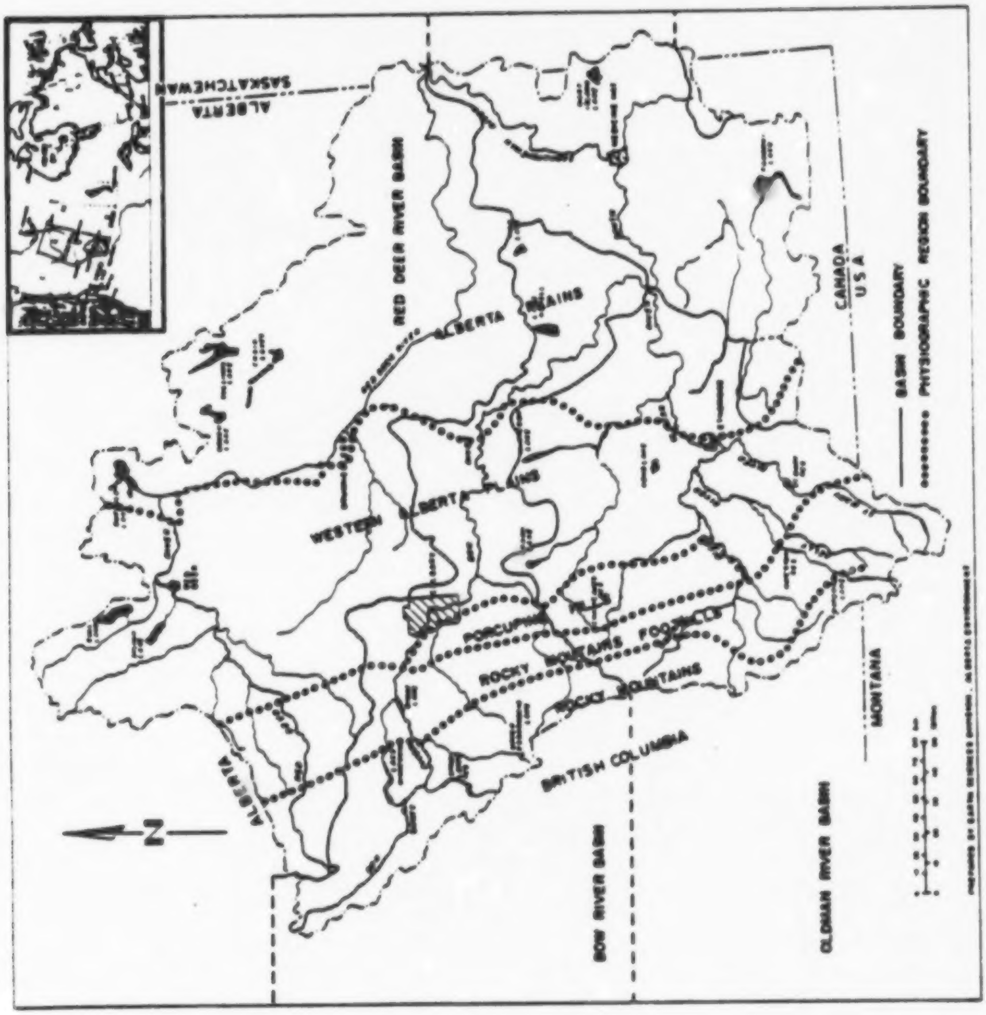

Fig. 1. Sub-basins and physiographic regions of the South Saskatchewan River Basin in Alberta

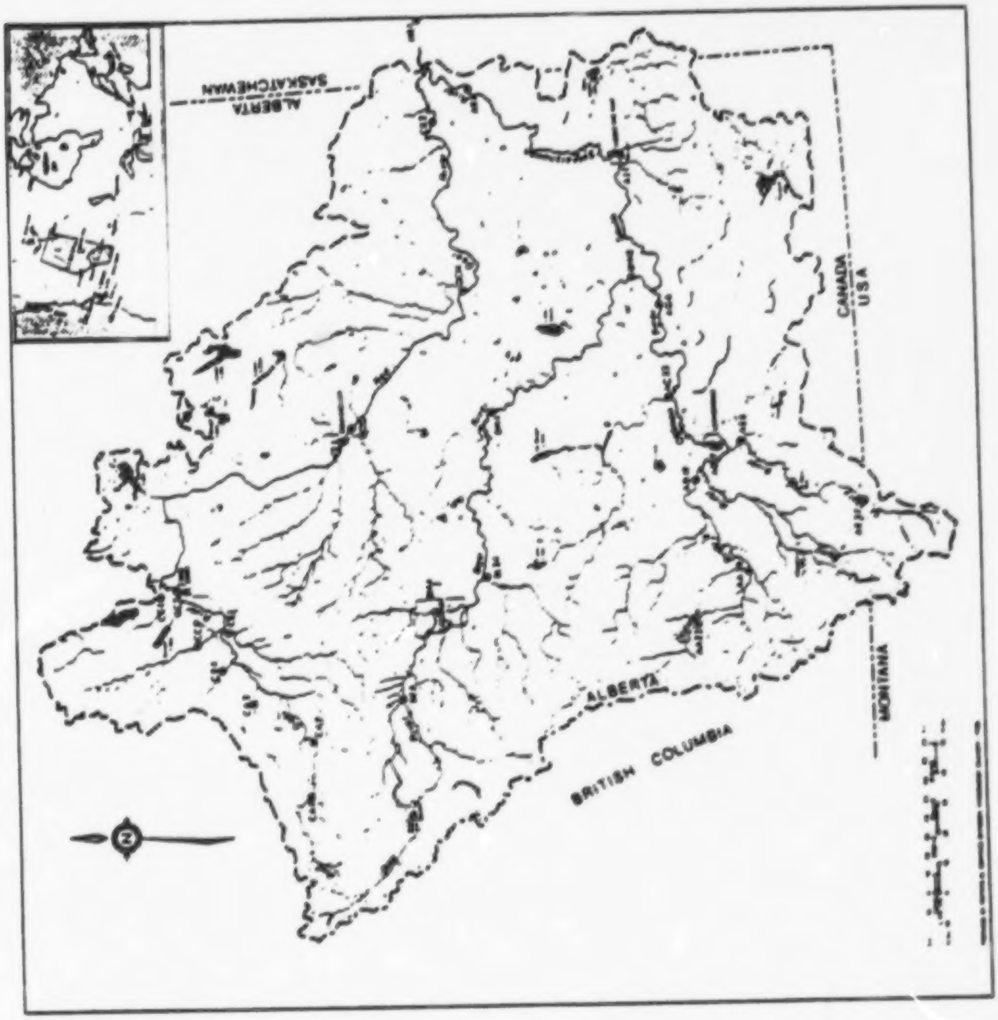

Fig. 2. Location of selected hydrometric stations in the South Saskatchewan River Basin in Alberta (see Table 1)

Table 1. Natural monthly mean flow at stream gauging stations and points of interest (hydrology branch) mean annual groundwater component (GWC)

| NAME | CODE | LOCATION | DRAINAGE AREA, km² | MIN. m³/s | MEAN m³/s | GWC m³/s |
|---|---|---|---|---|---|---|
| Oldman River near Waldron's Corner | AA23 | NE 10-10-02-5 | 1448 | 2.49 | 13.05 | 5.39 |
| Oldman River near Brocket | AA24 | SE 14-07-29-4 | 4398 | 8.18 | 41.14 | 13.23 |
| Oldman River near Monarch | AD19 | SE 01-10-24-4 | 8876 | 8.07 | 45.00 | 18.58 |
| Oldman River at Lethbridge | AD07 | NW 01-09-22-4 | 17000 | 24.00 | 112.45 | 28.06 |
| Oldman River near Mouth | AG06 | SW 24-11-14-4 | 27498 | 27.10 | 109.83 | 30.40 |
| St. Mary River at Int'l Bdry | AE27 | SW 05-01-25-4 | 1212 | 5.49 | 25.57 | 2.68 |
| St. Mary River near Lethbridge | AE06 | SW 19-07-21-4 | 3525 | 6.68 | 28.71 | 4.01 |
| Little Bow River near Mouth | AC23 | NW 11-11-19-4 | 5877 | 0.03 | 2.07 | 2.33 |
| Bow River at Banff | BB01 | SE 35-25-12-5 | 2209 | 8.07 | 40.00 | 6.12 |
| Bow River below Ghost Dam | BE06 | SE 15-26-05-5 | 6550 | 23.40 | 89.68 | 16.24 |
| Bow River at Calgary | B404 | NE 15-24-01-5 | 7863 | 25.00 | 93.76 | 17.95 |
| Bow River at Bassano Dam | BM04 | SW 02-21-19-4 | 20264 | 32.34 | 128.08 | 32.66 |
| Bow River near Mouth | BN12 | NW 33-12-12-4 | 25286 | 25.85 | 129.15 | 33.87 |
| Highwood River near Mouth | BL24 | NE 16-21-28-4 | 3988 | 3.26 | 24.86 | 9.62 |
| Red Deer River above Panther River | CA04 | NE 18-31-10-5 | 943 | 1.98 | 11.61 | 2.30 |
| Red Deer River below Burnt Timber Cr. | CA09 | SW 13-31-08-5 | 2246 | 4.96 | 22.94 | 6.03 |
| Little Red Deer River near Mouth | CB01 | SW 30-35-01-5 | 2564 | 0.48 | 5.52 | 3.19 |
| James River near Sundre | CA02 | SW 20-34-05-5 | 821 | 0.93 | 4.96 | 1.79 |
| Raven River near Raven | CB04 | SW 14-36-04-5 | 655 | 1.08 | 2.35 | 0.70 |
| Medicine River near Eckville | CC07 | NE 34-38-03-5 | 1906 | 0.28 | 4.53 | 2.71 |
| Blindman River near Blackfalds | CC01 | NW 14-39-27-4 | 1790 | 0.34 | 2.77 | 1.55 |
| Red Deer River at Red Deer | CC02 | SE 20-38-27-4 | 11600 | 8.58 | 49.00 | 20.08 |
| Red Deer River at Drumheller | CE01 | SE 11-29-20-4 | 24822 | 8.66 | 57.82 | 26.75 |
| Red Deer River below confl. of Rosebud | G CG | SW 28-28-19-4 | 29152 | 8.36 | 58.70 | 28.68 |
| Red Deer River at Dinosaur Park | G CH | SE 04-22-12-4 | 39064 | 7.68 | 60.63 | 30.12 |
| Red Deer River near Bindloss | CK04 | NW 25-22-03-4 | 44662 | 7.28 | 61.62 | 30.35 |
| South Sask. River at Medicine Hat | AJ01 | NW 31-12-05-4 | 56353 | 53.90 | 237.97 | 64.68 |
| South Sask. River at Highway 41 | AK01 | SW 33-20-01-4 | 65959 | 55.80 | 239.80 | 65.07 |
| South Sask. River near Lemsford, Sask. | HB01 | SW 10-24-23-3 | 119398 | 57.77 | 296.28 | 95.42 |

Table 2. South Saskatchewan River Basin below the Forks
Recorded and natural flows for 1977
(Prepared by Flow Forecasting Branch, Tech. Ser. Div.,
Alberta Environment)

| MONTH | | RECORDED FLOWS<br>acre-feet | NATURAL FLOW<br>acre-feet |
|---|---|---|---|
| January | | 165,400 | 98,366 |
| February | | 195,200 | 117,748 |
| March | | 231,900 | 187,380 |
| April | | 227,700 | 227,781 |
| May | | 288,000 | 599,116 |
| June | | 403,000 | 826,927 |
| July | | 203,000 | 503,900 |
| August | | 275,000 | 535,100 |
| September | | 239,400 | 461,100 |
| | TOTAL | 2,228,600 | 3,557,418 |

The Prairie Provinces Water Board is administering a river water sharing agreement by which naturally available flowing water is apportioned equally between Alberta and Saskatchewan. In the South Saskatchewan River basin a minimum of 1500 cfs (42.5 $m^3/s$), or 50% of the natural flow, whichever is less, must cross from Alberta into Saskatchewan. Mean monthly natural river flows have been calculated by the Hydrology Branch, Technical Services Division, Alberta Environment, for 57 stations and 44 points of interest along rivers and streams (Fig. 2 and Table 1). The calculated natural flows serve as a reference for recorded flows at these stations and thus allow calculation of the percentage of water used annually within Alberta. An example of a year with low flow measured at the Forks (the confluence of the Red Deer River with the South Saskatchewan River) is given in Table 2.

Precipitation and evaporation are two factors that play an important role in the hydrologic cycle. An isohyetal map (Fig. 3) showing the mean annual precipitation for the period 1912 to 1978 indicates that the highest values exist in the Rocky Mountains, the Foothills, and the Western High Plains in the Red Deer area. The lowest values of precipitation are found in the area of the Forks. Potential evaporation for bodies of open water was established to calculate water losses from reservoirs as a result of evaporation. Percentages of these limiting values were regarded as significant factors over land where evaporation takes place mainly as transpiration from plants. Also shown on Fig. 3 are the potential evaporation values; these values are highest in the southeastern region of the Basin, and lowest in the northwestern region. When superimposed onto each other, these contours and isohyets suggest the net precipitation available for runoff and infiltration.

The evaluation technique developed and used in this study involves simultaneous manipulation of several parameters or factors. The principal parameter is precipitation, which provides the input in the hydrologic equation. The output in this equation consists of runoff, evaporation and transpiration. Flow across basin bounderies either adds to or subtracts from the water resources within that basin. Parameters that control subsurface flow of water include the force of gravity, hydraulic conductivity of soil and bedrock and moisture retention capacity of the soil.

Precipitation that enhances groundwater flow is ponded meltwater and water from rainstorms of long duration. Evaporation consists of mainly evapotranspiration. The potential for evaporation exceeds precipitation in almost all areas but many factors prevent this from happening. Surficial runoff is that portion of precipitation which reaches streams overland. The largest quantities involved in runoff are meltwaters that do not penetrate frozen soil. Topographic controls prevent surficial water from crossing basin boundaries, but infiltrated water may do so if subsurface conditions permit.

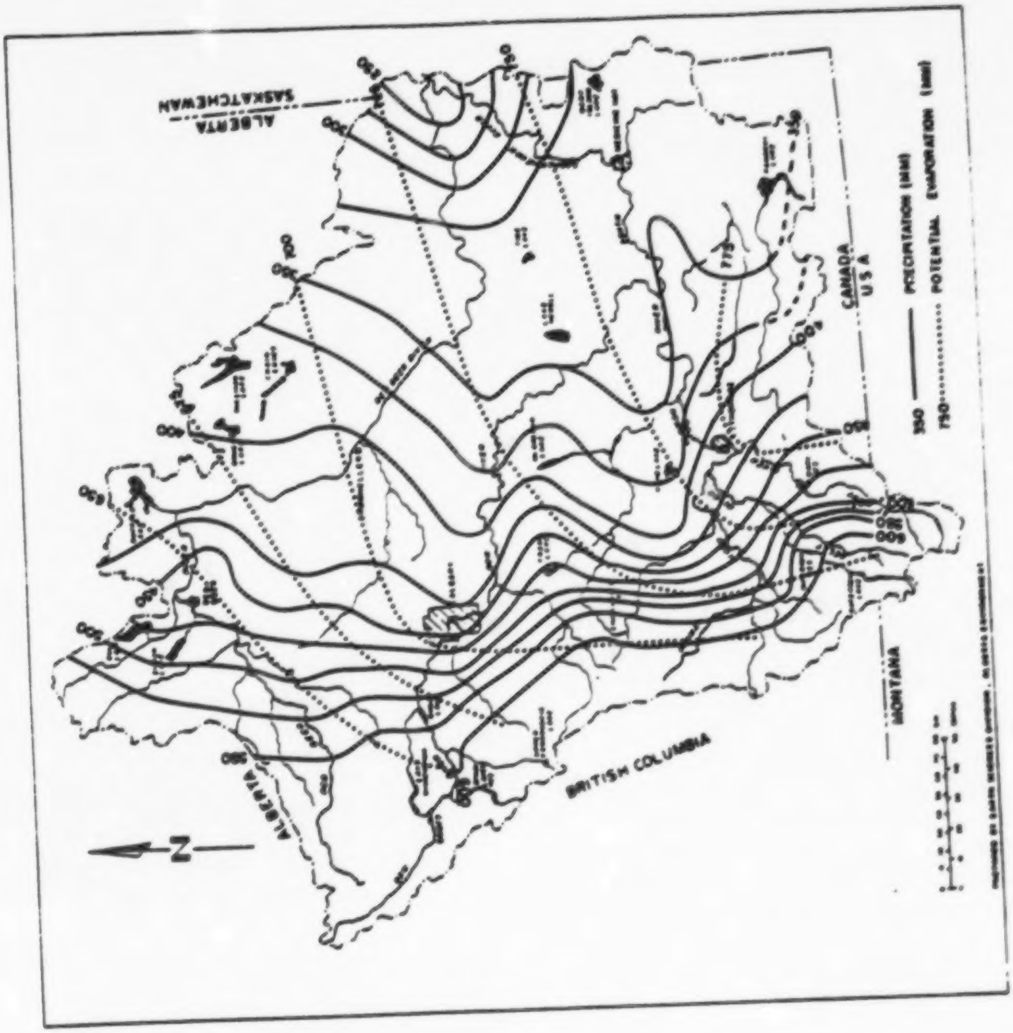
ALBERTA
SASKATCHEWAN
CANADA
U S A
MONTANA
BRITISH COLUMBIA
ALBERTA
N
350 —— PRECIPITATION (mm)
750 ······ POTENTIAL EVAPORATION (mm)

Fig. 3. Mean annual precipitation and potential evaporation in the South Saskatchewan River Basin in Alberta (from Hydrology Branch, Technical Services Division)

Water that has infiltrated into the ground and moves as groundwater may reappear downgradient either to evaporate or to augment streams or rivers as base flow . The hydraulic conductivity of the medium through which groundwater moves is a measure of its ability to transmit water. The moisture retention capacity of a soil relates to its property to absorb and hold water and is a factor mainly considered for rooting on irrigated lands. It serves also as a factor in the retention of infiltrated rain or meltwater and the release of this infiltrated water into the groundwater system long after precipitation has stopped.

Of all these factors, precipitation seemed to be the most reliable one and, coupled with evaporation, served as a reference parameter. The hydraulic conductivity of drift or bedrock was not widely measured (Chorley, 1982; Hendry, 1980) but fairly reliable estimates could be arrived at from the description of these materials identified on published soils and surficial geology maps. For the present purpose three ranges of hydraulic conductivity were chosen and mapped. The middle range ($k = 10^{-5}$ to $10^{-8}$cm/s) is mainly represented by tills and silty clay loam. The high range ($k>10^{-5}$ cm/s) is represented by silty sands, loess, sands and gravels, alluvials, colluvials and talus. The low range ($k<10^{-8}$ cm/s) is represented by clays and unfractured clay tills.

In the search for groundwater throughflow, the base flow, which is approximately equivalent to low stream discharge, was picked from stream gauging records. Although the major rivers always flowed, many of the smaller streams and tributaries were dry during the winter because the water table had fallen below the stream bed. The number of stations for minimum base flow was therefore reduced. However, calculated mean monthly minimum flows were available. The incremental increase of flow downstream from one station to the next would approximately represent the winter contribution of groundwater from recharge areas. However, the groundwater contribution during the rest of the year could not be determined in this manner.

A method was devised to determine the average rate of groundwater throughflow and to identify corresponding recharge areas. The first step was to construct a number of regional geological cross-sections referenced to sea level. The groundwater flow net and the water table were then superimposed on the cross-sections. Water levels were obtained from drillers' well logs and hydrogeological maps (Alberta Research Council, Edmonton). Areas of recharge were then picked along the ground surface of this section. With the aid of topographic and hydrogeologic maps, recharge areas were identified between and beyond the regional hydrogeological cross-sections.

The second step was to relate the measured base flow of a river's regime with the corresponding recharge area. The result was a factor that approximated an overall hydraulic conductivity which compared reasonably well with those obtained from field along the Milk River. The hydraulic gradient is northward so that

Table 3. Physiographic distribution of groundwater recharge ($m^3/s$)

| SUB-BASIN | | PHYSIOGRAPHIC REGION | | | |
|---|---|---|---|---|---|
| Area | Total Recharge | Rocky Mountains | Foothills | Western Alberta Plains | Alberta Plains |
| Red Deer River Basin | 30.39 | 3.87 | 5.39 | 17.14 | 3.99 |
| Bow River Basin | 33.90 | 23.12 | 8.19 | 2.33 | 0.26 |
| Oldman River Basin | 30.40 | 15.80 | 9.20 | 4.60 | 0.80 |
| South Saskatchewan River Basin | 0.80 | N.A. | N.A. | N.A. | 0.80 |
| Total Recharge | 95.49 | 42.79 | 22.78 | 24.07 | 5.85 |

much of the basin where stream gauging records were either unavailable or quite unreliable. The assessment of hydraulic conductivity in areas where measurements were not available lacked in precision so that any relationship could not possibly be checked where streamflow was zero. However, the precipitation and evaporation were reasonably well established throughout the basin. A relationship was therefore developed, employing precipitation and evaporation and the recharge area explicitly, and the hydraulic conductivity implicitly, to establish an average rate of recharge and consequent discharge as base flow. The close agreement of the results showed that a simple multiplication of precipitation, recharge area, a dimensionless factor that relates to evaporation and precipitation and a factor allowing for the presence of materials of greater or lesser hydraulic conductivity could be employed to calculate average groundwater throughflow from large areas (Table 3).

Seasonal variations in groundwater flow are pronounced in the western areas, especially in the Rocky Mountains and the Foothills. Both surficial runoff and underground throughflow occur mainly over a short distance and a short interval of time, and are aided largely by steep gradients in surficial topography. The relatively permeable colluvials and open rock fractures can rapidly transmit large quantities of water. Much of that activity would take place during spring and early summer, less towards the fall, and very little after freeze-up.

In the Western Alberta Plains, the groundwater flow activities are subdued, mainly because of low topographical relief. In addition to the properties of the surficial material, mainly glacial tills, the permeability and structural conditions of bedrock near the surface area are significant factors. The sandy facies of the thick Paskapoo Formation in the northern areas can absorb and release large quantities of water. In the southern areas of the Western Alberta Plains, the sandy members of the Paskapoo Formation are replaced by silty members of the Willow Creek Formation. Other bedrock present includes the Horseshoe Canyon and the St. Mary Formations which contain bentonitic sandy lenses in shales. The Blood Reserve Sandstone near Lethbridge is large enough to influence groundwater flow. Bedrock of low permeability is exposed in the St. Mary River basin. Northwest of Lethbridge surficial sands and gravels exist that could store and release large quantities of groundwater.

The Alberta Plains take up the eastern half of the basin in question. Precipitation is low and evaporation is high so that little precipitated water is left for groundwater recharge. Vast areas have only a thin soil or till cover and much of the bedrock is composed of clayey shale and thin bentonitic sandstone layers so that infiltrated water moves very slowly.

The topographic boundaries of the South Saskatchewan River basin coincide, by and large, with the boundaries of the groundwater systems considered here. Lithostratigraphy in the Sweetgrass Arch exposes a section of the porous Milk River sandstone along the Milk River. The hydraulic gradient is northward so that river water must recharge into this sandstone, flow north and northwest, seep upward through the clayey Pakowki Formation and the clayey and sandy layers of the Foremost and Oldman Formations, and finally discharge into both the Oldman River and the South Saskatchewan River. The quantity of discharge calculated is 0.3 $m^3/s$ maximum. Another area where influx may occur is along the northeastern boundary where an estimated maximum 0.08 $m^3/s$ could possibly be added to the groundwater discharging into the Red Deer River.

Irrigation has been practised in southern Alberta since early this century. The Bow River and several rivers in the Oldman River basin have been dammed to store water for large scale irrigation. A total of 1,082,634 acres (438,142 hectares) is presently available for irrigation for which 2,128,200 acre-feet (2.633 $km^3$) of water is licensed for diversion from the rivers for one growing season. This licensed quantity is equivalent to an average surcharge of 0.6 m accumulated at a rate of 83.2 $m^3/s$ over 12 months.

According to Hendry (personal communication), not all available water is being applied on the land, however. For example, in the Bow River Irrigation District, only 40% of the available water (0.65 m) was applied. Of this, 0.1 m percolated below the root zone as recharge to groundwater. Irrigable land in the Bassano-Lethbridge area has a relatively permeable base so that much of this 0.1 m recharge could return to the rivers. In irrigable areas underlain by a less permeable base only a small fraction of recharge would reach the rivers as groundwater. Instead, much of the recharge will come to the surface and evaporate. Therefore, an estimated maximum of 15% in certain areas and an overall average of 4% (3.3 $m^3/s$) of water licensed for diversion would return as groundwater to the rivers.

The chemical composition of groundwater is reflected by the residence time of the water, the mineral environment and, sometimes, the origin and history of an aquifer. The low mineralization of groundwater found in the Rocky Mountains, the Foothills and portions of the Western Alberta Plains indicates short residence time and active, shallow flow. Bicarbonate type waters predominate. In the rest of the Plains the groundwater is noticeably mineralized, which reflects a longer residence time, often slow deep flow and ample contact with minerals. In addition, the hydraulic conductivity is generally low. Sulphate type waters and, in a few areas, even chloride type water are dominant. However, only little of that water reaches streams and rivers. Shallow, less mineralized water will tend to flow faster and reach the rivers sooner. Waterlogging and salinization of soil is on the rise as a result of irrigation. Of the more than 400,000 ha irrigated, some 81,000 ha have experienced deterioration of the soil, mainly in the form of salinization (Vander Pluym, 1982). Leaking canals are responsible for many hectares gone out of production.

Groundwater use in the Basin is restricted to mainly rural domestic and livestock purposes. The estimated average rate of extraction is 1.12 $m^3/s$ (based on the consumption of 1.5 $m^3/d$ per well) from a total of 64,215 reported wells. The actual number of wells in existence and in use is considerably greater but the total withdrawal of groundwater probably is still less than 2 $m^3/s$.

With the clearing of bush to make way for agricultural enterprises the water table has fallen. This would indicate that some of the water which originally infiltrated to recharge the groundwater systems is now lost to the atmosphere.

It is concluded that the method developed to calculate the regional groundwater component of river or stream flow yields results probably within an accuracy of ±25% considering the lack of precise data. The method may be inadequate for application to local groundwater regimes. Most of the groundwater involved in streamflow is shallow (less than 100 m) so that both surficial materials and shallow bedrock critically influence groundwater flow. The net input from precipitation is determined at and below the ground surface. Except in gravel, karst or fractured rock environments the motion of groundwater is slow and fairly steady. With an average throughflow rate of 95 $m^3/s$, groundwater is a significant component of streamflow in the study area of the South Saskatchewan River Basin.

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## SESSION III: RECLAMATION OF WATER RESOURCES

Chairman
Dr. Frank F. Munshower
Director
Reclamation Research Unit
Montana State University
Bozeman, MT

# SPOILS AQUIFER RESATURATION FOLLOWING COAL STRIP MINING

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## ABSTRACT

Coal beds in the Tongue River member of the Fort Union Formation are a source of small groundwater supplies in the shallow bedrock in much of southeastern Montana. Strip mining of these beds removes the coal and replaces it with overburden spoils. With time, aquifers are reestablished in a rubble zone at the base of the spoils. The rate of resaturation and thickness of the resaturated layer depends on physical characteristics of the spoils, method of replacement, and availability of groundwater for recharge. Three major sources of groundwater for spoils recharge are adjacent, unmined coals, underlying aquifers undisturbed by mining, and surface infiltration.

Spoils recharge at West Decker comes mainly from adjacent, unmined coal beds that subcrop under the Tongue River Reservoir. A secondary source is underlying, unmined coal beds. Surface infiltration is considered insignificant due to the thickness and fine texture of the spoils.

Recharge at the Rosebud mine is predominately from adjacent, unmined coals. In localized areas, recharge to the spoils is enhanced by thin spoils, coarse textured spoils, and the presence of surface water bodies.

## INTRODUCTION

Recharge of mine spoils aquifers has generally been attributed to infiltration and downward percolation of moisture from the soil surface (Wayne Van Voast, personal comm.). Laws governing strip mine reclamation in Montana were written with this concept in mind, and little emphasis has been given to spoils recharge from lateral or subspoils sources. However, under some conditions, given the low precipitation and high evapotranspiration rates found in coal mining areas of the state, it is unlikely that surface recharge plays a significant role in spoils aquifer recharge. In this paper, two coal mining areas are considered, Western Energy Company's Rosebud Mine at Colstrip and Decker Coal Company's West Decker Mine near Decker.

The two areas have similar climates with comparable rates of precipitation and evapotranspiration, which effectively limit the amount of surface recharge. However, the potential for recharge from resources adjacent to and beneath spoils is strikingly different. The West Decker mine has two sources of groundwater recharge to the spoils aquifer. The first is unmined coal in hydrologic contact with the Tongue River Reservoir and Tongue River alluvium. The second is coal beds beneath the spoils which have piezometric heads higher than the coals being mined.

Sources of groundwater recharge at the Rosebud mine are less abundant. There are no major surface water bodies in the vicinity bodies (sediment ponds) are generally located downgradient from spoils areas and have little effect on spoils recharge. A small impoundment in Pit 6 appears to be associated with a local zone of recharge. Secondly, vertical hydraulic gradients are downward; there is no upward flow to the spoils. The main source of recharge to spoils is water from adjacent coal beds.

## LOCATION OF STUDY AREAS

The West Decker mine is located at the mouth of the Pond Creek drainage in Township 9 South, Range 40 East, about 4.8 km (3 miles) northeast of the Decker Post Office in Big Horn County (Fig. 1). Portions of the Tongue River Reservoir and floodplain lie within .8 km to the east. The Rosebud mine lies in Townships 1 and 2 North, Range 41 East in Rosebud County (Fig. 2). The mine straddles the East Fork Armells Creek drainage and also occupies the headwaters of the Cow Creek, tributary to Rosebud Creek to the east.

## METHODS AND MATERIALS

Strip mine permits and permit applications contain detailed descriptions of the hydrology of active and proposed mine areas, including the quantity and quality of groundwaters within the adjacent to the active and proposed mine areas, and changes in the hydrologic system that have occurred as a result of mining. Mining companies also submit semi-annual reports of water level and water chemistry data collected during the previous wateryear. Reports on the hydrology of the West Decker and Western Energy prepared by Van Voast and others of the Montana Bureau of Mines and Geology were also utilized. Representative monitoring wells in coal and spoils aquifers for each mine were selected and hydrographs utilizing all available water level data were plotted. The graphs were analyzed to correlate water level changes with seasonal fluctuations, pit openings and backfilling operations. Total dissolved solids, and common ion concentrations of water from spoils aquifers and adjacent coal beds were compared at West Decker to determine the source of groundwater in the spoils aquifers.

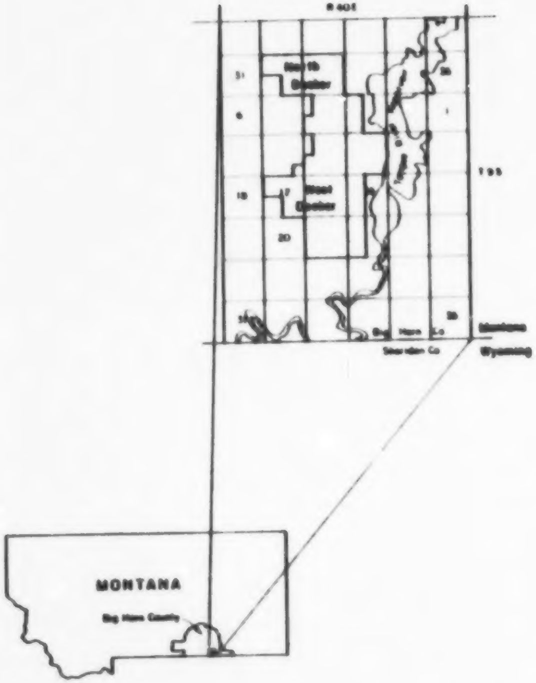

Fig. 1. Location of the West Decker mine.

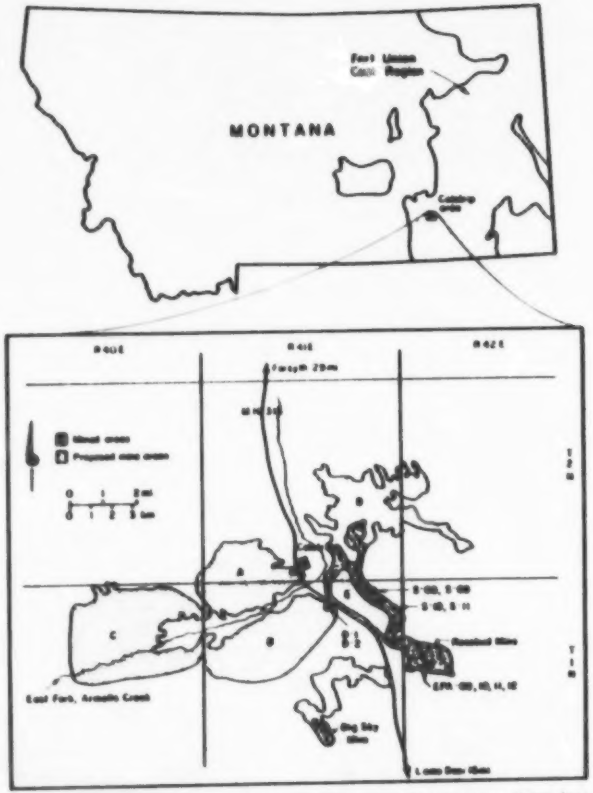

Fig. 2. Locations of Colstrip, mined areas, and proposed mine areas. Taken from Van Voast, Hedges and McDermott, 1977

# RESULTS

## West Decker

Mining at West Decker began in the summer of 1972 with the opening of a test pit. By late summer, 1973, the first horseshoe-shaped mine cut was completed through the mine area. At that time, only the D-1 coal was being mined. An interior box cut was opened beginning in late 1981. In this cut, both the D-1 and D-2 coal are being mined, with mining of the D-2 commencing in 1982 (Fig. 3 and 4).

Spoils recharge at West Decker comes from three sources: seasonal recharge from the Tongue River Reservoir, recharge from unmined coal (D-1) adjacent to the spoils, and recharge from an unmined coal bed (D-2) more than 6.1 meters (20 feet) below the spoils. Hydrographs of the following wells and associated aquifers were constructed: WR-06 (D-1), WR-07 and DS-2A (D-2); and DS1A, DS3, and DS6A (Spoils).

Analysis of the hydrographs leads to the following observations regarding spoils recharge from the reservoir: 1) Recharge peaks partially coincide with rising reservoir stage and increased rainfall in later spring and early summer (May-July), but are somewhat complicated by mining and dewatering activities (Fig. 5 and 6). 2) Recharge peaks of unaffected coal wells to the west occur slightly earlier (April-June) in response to the earlier spring snow melt. (The spoils wells within the mine area are physically separated from the coal wells to the west by the mine pit, eliminating any possible connection between the seasonal reservoir effects and seasonal spring melt effects). 3) Pit inflows were observed along the east end of the interior box cut and the main pit, and from the fault plan of the southeast boundary fault into the mine pit. 4) Water levels in the D-1 showed a rapid response (Fig. 5) to opening of the original pits. Even before water levels began to recover, a seasonal effect of the reservoir stage is evident during 1974-1977. Opening of the interior box cut in 1981 again produced a rapid decline in the D-1 water level. 5) The D-2 coal showed a distinct decline with the opening of the original mine pits in 1972. Its piezometric head reached a stable level with seasonal fluctuations from mid-1976 until late 1981 in the D-2 coal dropped sharply.

Evidence for recharge of spoils by unmined coal adjacent to the spoils includes observations of inflows to the interior box cut from the D-1 coal, overburden and D-1/D-2 interburden. Inflows from the D-1, overburden and the southeast boundary fault plane are also present in the southeast end of the main pit.

Upward leakage from the D-2 coal is suggested by water levels higher in the spoils than in laterally adjacent sources.

The chemical composition of water from both the spoils and coal aquifers is a sodium bicarbonate type, with the spoils waters

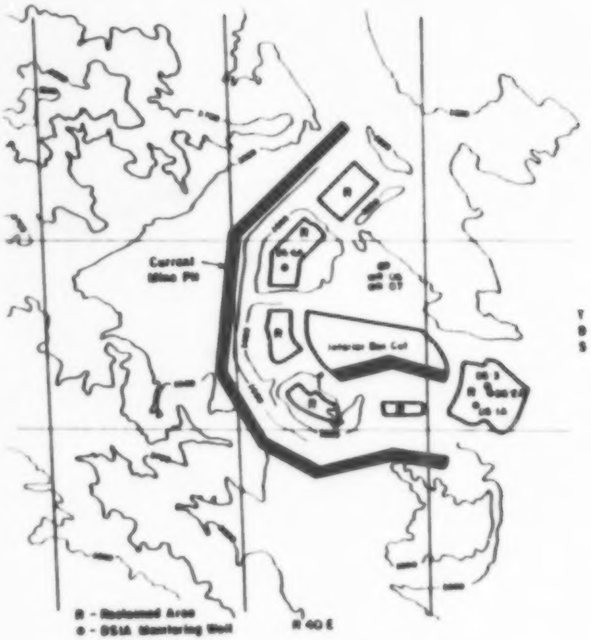

Fig. 3. Existing topography of the West Decker Mine, including current mine pit, interior box cut, reclaimed areas and monitoring wells

From Draft EIS, West Decker Mine, Montana Dept of State Lands, 1980

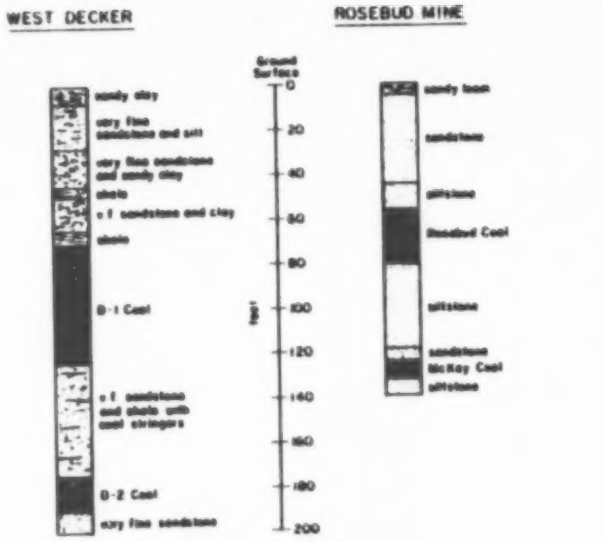

Fig. 4. Typical stratigraphic columns for the West Decker and Rosebud mines

From West Decker Mine Permit #81001 and Western Energy Mine Permit #80003

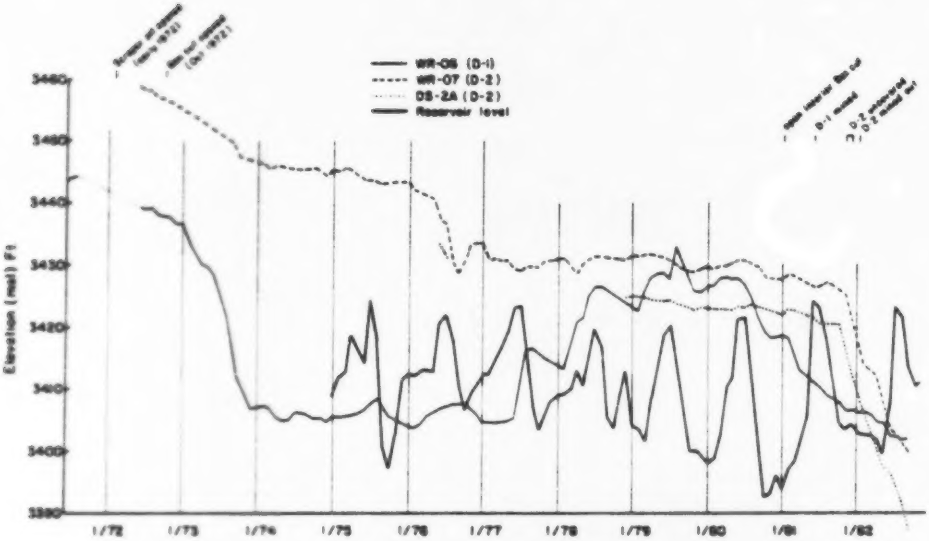

Fig. 5. Hydrographs of D-1 and D-2 Coal Aquifers at West Decker for period July, 1972 to September, 1982

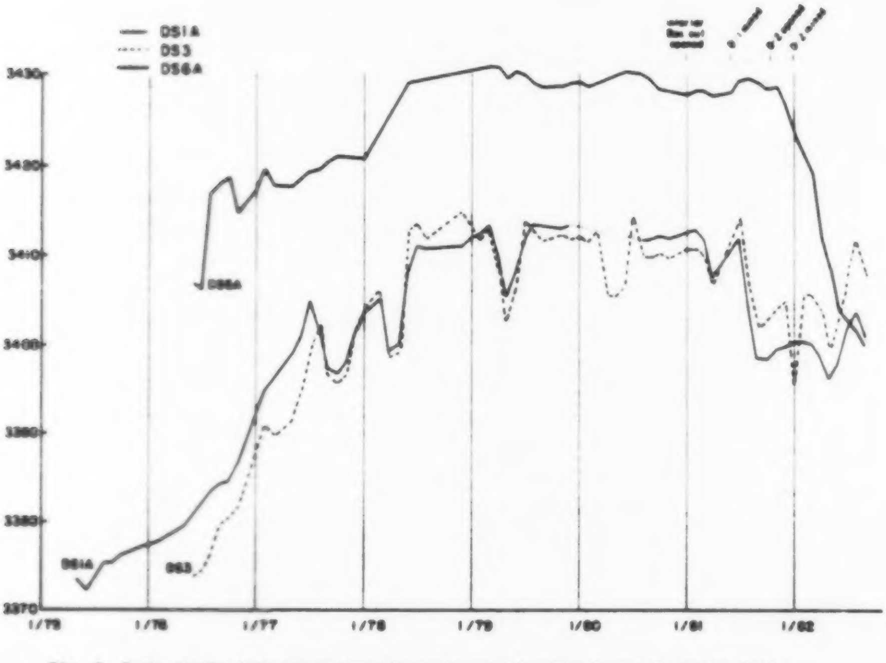

Fig. 6. Spoils Aquifer Hydrographs at West Decker for period May, 1975 through September, 1982

containing higher concentrations of calcium, magnesium, and sulfate. The similar water types may indicate upward migration from the D-2 whereas the higher concentrations of other ions indicate leaching of the spoils materials.

Water levels rose steadily until 1978, when the levels stabilized. Seasonal recharge peaks are evident in June and July of years 1978-1981. These are coincident with water levels in coal monitoring wells in the same area between the mine spoils and the reservoir. In 1981, water levels in both the spoils and coal wells in the mine interior began dropping in response to the opening of the interior box cut.

These lines of evidence show a strong interrelation between water levels in the spoils, coal aquifers and the Tongue River Reservoir. The spoils aquifers are being recharged both laterally and from beneath, but the major factor controlling water levels in the spoils aquifer is the Tongue River Reservoir stage. Water level fluctuations in spoils and coal wells in the interior of the West Decker mine strongly reflect water level fluctuations in the reservoir, whereas wells west of the active pit, isolated from the reservoir, show an earlier yearly response related to recharge from spring snowmelt.

### Western Energy

Mining began at Colstrip in 1924 when the Northern Pacific Railroad mined coal to fuel steam-powered locomotives. In 1959, Montana Power Company bought the Colstrip townsite and the mining leases owned by Northern Pacific, and in 1968, Western Energy Company began mining in the Pit 6 area. Active mining has since extended into Areas A, B, C and E, and an application has been submitted for Area D (Fig. 2).

The geology controlling the groundwater hydrology of the Rosebud mine differs from the West Decker mine. The coal beds are shallow aquifers, but there are no surface water bodies of sufficient size to significantly affect spoils aquifer recharge. The valley of East Fork Armells Creek, an ephemeral stream in the mine area, contains only small amounts of alluvium which could store water and provide recharge to mine spoils. One local source of spoils recharge water is a small pond in the Pit 6 area. Sediment ponds also contribute to groundwater recharge, but are generally located downgradient from mined areas and have little affect on mine spoils.

Surface infiltration is a more significant recharge factor at the Rosebud mine, especially in areas of thin overburden. The Rosebud overburden is coarser textured, and the clays are less sodic, (Western Energy SMP #80003 and Decker Coal Company SMP #81001) indicating a greater potential for infiltration and downward movement of water (Fig. 4).

Lateral recharge from unmined Rosebud coal and vertical recharge from the underlying McKay coal may contribute to spoil recharge, although definitive evidence is lacking for recharge from the McKay. Three sets of hydrographs of well pairs finished in the spoils and McKay coal were analyzed. The well pairs were chosen because of their long periods of record and their curves are believed to be typical for spoils and McKay wells in their respective locations. Two pairs of wells are along the eastern edge of the old Northern Pacific spoils (Fig. 2, 7, 8), two pairs are located adjacent the impoundment in Pit 6 (Fig. 2, 9), and one pair is in the older, reclaimed portion of Area B (Fig. 2, 10). Interburden thicknesses range from 0.6 to 4.0 m (2 to 13 ft) in the Northern Pacific and Pit 6 areas, to 6.1 to 7.6 m (20 to 25 ft) in Area B. All the well pair hydrographs indicated a good hydrologic connection between the spoils and underlying McKay coal.

In the first area, well pairs S-08 (McKay)/S-09 (Spoils) and S-10 (Spoils)/S-11 (McKay), with 0.6 to 1.8 m (2 and 6 ft) of interburden, respectively, show that the McKay head is generally greater than the spoils head (Fig. 7, 8). At those locations, the spoils tend to be dry, becoming only partially saturated during periods of higher than normal precipitation. The McKay coal shows a similar response to precipitation patterns, but remains partially saturated during extended dry periods. The data are inadequate to indicate whether the source of the spoils water recharge is surface infiltration, lateral inflow derived from unmined coal or recharge from the McKay coal. Undoubtedly, all three play parts of varying significance to spoils recharge.

Part of the reclaimed area in Pit 6 drains internally to a perennial pond. The pond is the main source of recharge to the spoils, and possibly to the McKay coal, in that area. The soils and overburden in the Pit 6 area are very sandy, and contribute to a higher recharge rate there. The interburden between the spoils and McKay coal is about 4.0 m (13 ft) thick.

Fig. 9, hydrographs for McKay/spoils well pairs EPA-09 and 10 and EPA-11 and 12, shows that shortly after the wells were installed, piezometric levels in the spoils rose above those in the McKay, and have remained higher to the present. This suggests a downward movement of groundwater into the spoils from the pond. Response to yearly precipitation levels is evident. Years 1975, 1976, 1978 and 1979 show relatively rapid rises in the water levels, compared to a more gradual rise in years of lower precipitation. Both the spoils and McKay show the response, but it is more pronounced in the spoils because of higher water levels in wet years increased the rate of recharge. Thus, a perennial source of surface water, coarse textured soil and spoils materials, higher piezometric head in the spoils and a greater response to precipitation events in the spoils indicate surface recharge is the main factor in spoils recharge in the Pit 6 area.

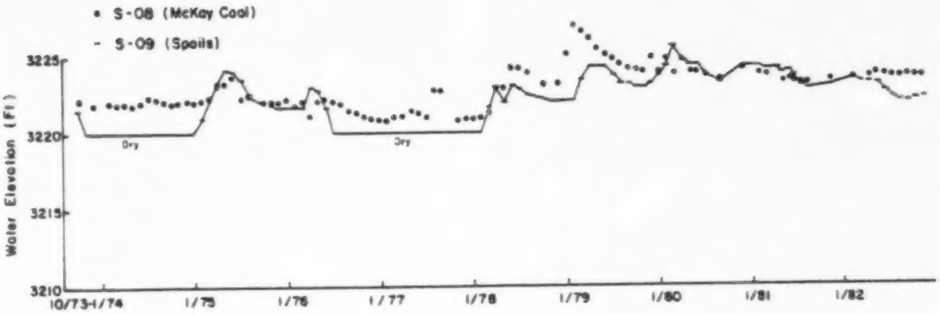

Fig. 7. Hydrographs for wells S-08 and S-09, Rosebud Mine, for period October, 1973 to October, 1982.

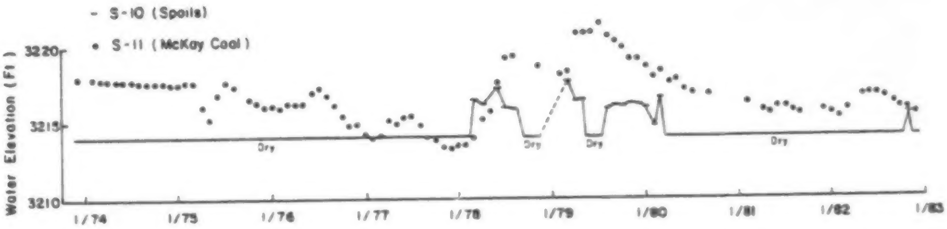

Fig. 8. Hydrographs for wells S-10 and S-11, Rosebud Mine, for period October, 1973 to December, 1982.

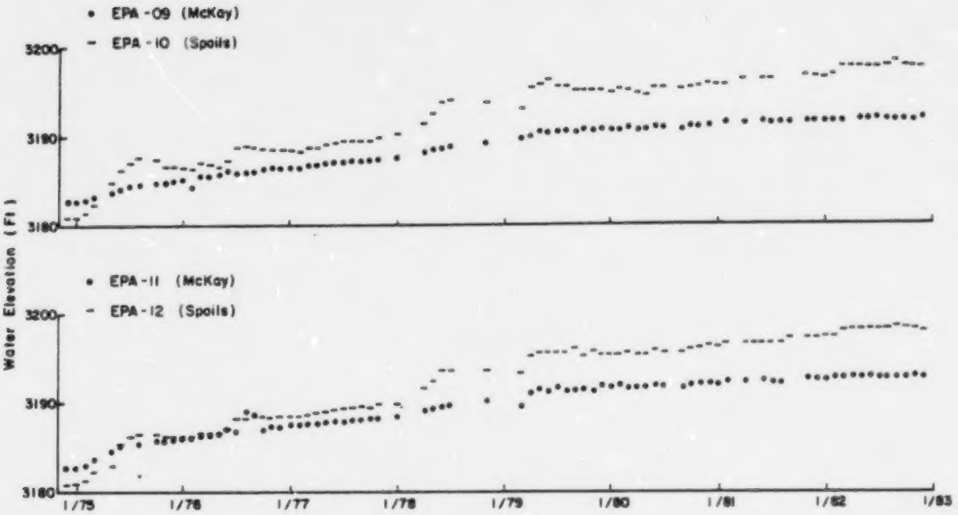

Fig. 9. Hydrographs for wells EPA-09, 10, 11, 12, Rosebud Mine for period December, 1974 to December, 1983.

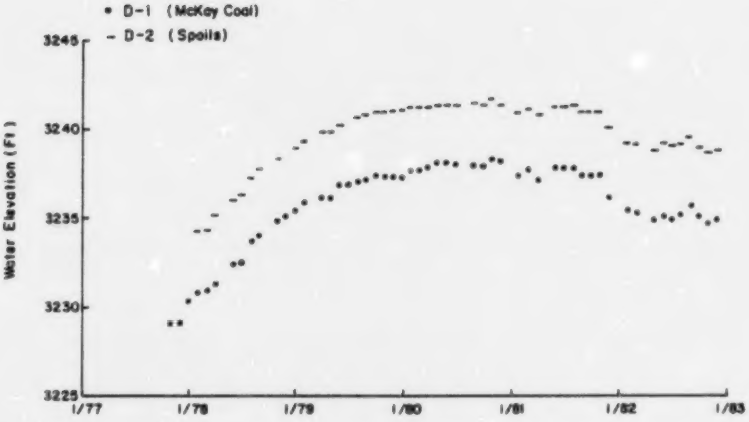

Fig. 10. Hydrographs for D-1 (McKay Coal) and D-2 (Spoils) wells for period November, 1977 to December, 1982 Western Energy.

The third area analyzed is in the older portion of Area B spoils. The spoils/McKay interburden is 6.1 to 7.6 m (20 to 25 ft) thick, and the area lies approximately on a north-south trending groundwater divide. Unmined Rosebud coal is present about 91 to 122 m (300 to 400 ft) to the northeast. The hydrographs for well D-1 (McKay coal) and D-2 (Spoils) (Fig. 10) show that water levels in both the spoils and McKay coal rose steadily from the beginning of 1978 until about the middle of 1979. They remained stable until late 1981, after which they declined about 1.5 m (5 ft) to a lower, relatively stable level in the spring of 1982. During the period of record, the spoils head has consistently been 1.8 to 2.4 m (6 to 8 ft) higher than the head in the McKay coal.

The spoils are about 24 m (80 ft) thick in this area, so it is unlikely that surface inflitration has had a large effect on the spoils' recharge. Given the head differential between the spoils and McKay coal, it is also unlikely recharge is coming from the McKay coal. The most likely source of recharge is adjacent unmined Rosebud coal. The smoothness of both the spoils and McKay curves indicates a constant rate of recharge to both the spoils and McKay coal following mining and spoil replacement.

## SUMMARY AND CONCLUSIONS

Recharge to coal mine spoils in southeastern Montana comes from three principal sources: 1) laterally from unmined coal beds; 2) from lower aquifers with a higher piezometric head than the spoils; and 3) surface infiltration. The presence or absence of surface water bodies in the vicinity of mine spoils influence the rate of recharge from all three factors.

At West Decker, recharge is primarily from adjacent, unmined coals that subcrop under the Tongue River Reservoir and underlying coal beds with higher heads. Surface recharge is insignificant because of the thickness and fine texture of the spoils. At the Rosebud mine, recharge is predominantly from adjacent, unmined coal in Area B, although in other areas surface infiltration is enhanced by thin spoils, coarser texture of the spoils, and small, surface water bodies in certain parts of the mine. Recharge from the underlying McKay coal is insignificant.

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# CLASSIFYING AQUATIC RESOURCES:
# A QUANTITATIVE APPROACH

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## ABSTRACT

Twenty-seven water quality parameters from 41 coal and bentonite surface mine and livestock ponds were used to show how quantitative, multivariate procedures could be used to classify aquatic resources. Data were subjected to polar ordination to define the groups of ponds based on water quality criteria, followed by analysis of variance and discriminant analysis to estimate the classification functions and coefficients. The classification error rate was about 8%. If proper considerations are given to the requirements and needs of the classification system, adequate data collection and analyses should yield a quantitative classification system which meets the goals of resource managers.

## INTRODUCTION

Recent demands placed on resource managers (i.e., National Forest Management Act, Forest and Rangeland Renewable Resources Planning Act, land management planning) have led to the need for quantitative fish and wildlife habitat classification systems. In the past few years, several classification systems of aquatic resources have been developed based on quantitative measurements (Pfleiger et al., 1981; Lotspeich and Platts, 1982). However, these systems do not quantify the quality of the habitat on a site-specific basis. Attempts to classify the quality of habitats have led to the development of indices (Goodnight, 1973; Chutter, 1972).

Ordination procedures for grouping similar stands of vegetation have been described by Mueller-Dombois and Ellenberg (1974: 277-302). The use of cluster analysis to determine synecological units in the ponderosa pine habitats, in the Black Hills of South Dakota, by Thilenius (1972) is one of several studies which used cluster analysis procedures to define vegetation units. Pflieger et al. (1981) used cluster analysis to define stream habitats in Missouri, based on 10 physical attributes of the stream, and then reclassified the streams based on t-tests of a constancy-fidelity index of fish species. MacCracken and Hansen (1982) used discriminant analysis to reclassify habitats used by blacktail jackrabbit (Lepus californicus) and nuttall cottontail (Sylvilagus nuttalli). More recently, MacCracken et al.[1] used the ordination procedures described in Mueller-Dombois and Ellenberg (1974) to define plant community associations (habitats) and the results of discriminant analysis to quantify the plant community descriptions and estimate the accuracy of the classification. The procedures cited above have been used to classify impoundments created from surface mining and damming of water drainages, based on the measurement of the water quality parameters in the impoundments. This paper presents an approach to the use of quantitative data to classify impoundments on the northern Great Plains.

## STUDY AREA AND METHODS

The sites used in this study were considered to be representative of impoundments on the northern Great Plains. Coal surface mine impoundments were located throughout the region on coal mine sites. Bentonite surface mining is restricted to a localized area, and sites selected for study were representative. Livestock watering impoundments were included because they were created with a minimum of disturbance (Anderson et al., 1979) and because many of these types of impoundments have been constructed on the northern Great Plains (Bue et al., 1964).

Forty-one water impoundments on the northern Great Plains were selected for this study. Near Colony, Wyoming (Fig. 1), 12 impoundments created by bentonite clay surface mining (bentonite surface mine impoundments) were selected. Impoundments created by coal surface mining (coal surface mine impoundments) were distributed as follows: six near Firesteel, South Dakota; seven near Sheridan, Wyoming; one near Gascoyne, North Dakota; and six near Beulah, North Dakota. Nine livestock watering impoundments were selected for comparison with at least one impoundment at each of the previous locations.

Measurements of 27 water quality parameters were collected from each impoundment. Single grab samples from each impoundment were analyzed for aluminum, arsenic, cadmium, chromium, cobalt, copper, iron, lead, maganese, mercury, selenium, silica and zinc. Over a three-year period, specific conductivity and pH were measured in the field; depth of 0.5% light penetration was measured with an underwater photometer; and water samples were collected and analyzed for bicarbonate, carbonate, calcium, chloride, magnesium, nitrate, phosphorus, potassium, sodium, sulfate and total Kjeldahl nitrogen.

Averaged data for each impoundment were analyzed. Data were subjected to polar ordination (Gauch, 1977) and ISODATA cluster analysis (Ball and Hall, 1969) to group the impoundments based on the parameters measured. Stepwise forward-backward discriminant

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[1] MacCracken, J. G., D. W. Uresk, and Hansen, R. M. "Plant community variability on a small area in southeastern Montana," manuscript in preparation submitted to Great Basin Naturalist.

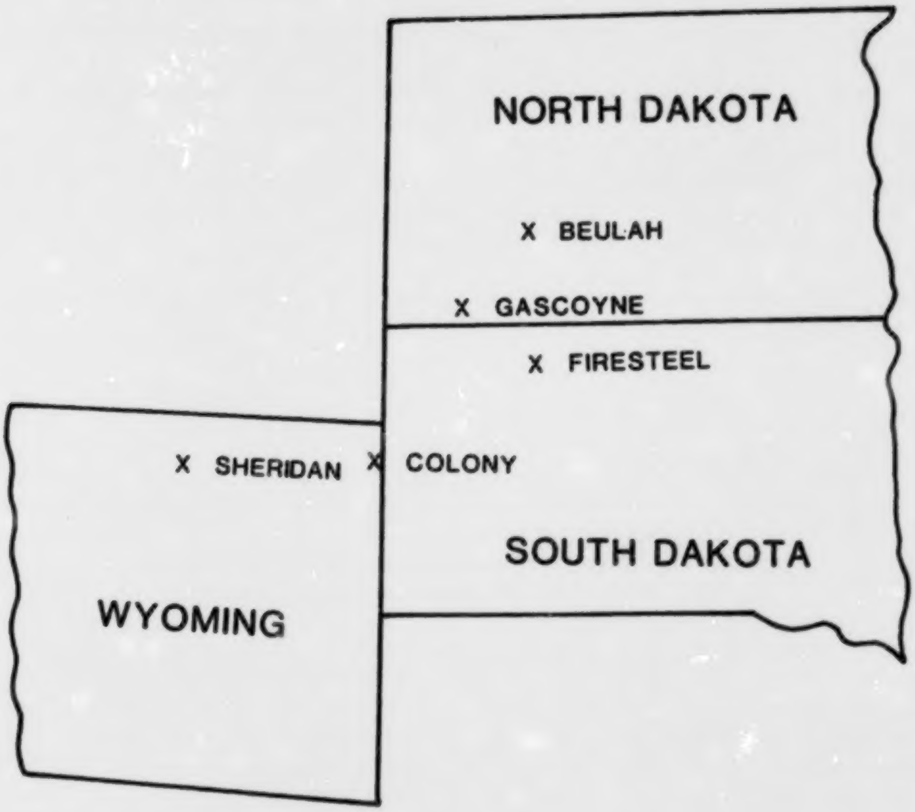

Fig. 1. Map of water impoundment locations.

analysis (Nie et al., 1975) was then performed to estimate the reliability of the separations among a group of impoundments, to analyze which parameters were important in separating the impoundment groups, and to estimate the coefficients for classifying impoundments based on measurement of a limited number of water quality parameters. The probability level set before a parameter could enter the analysis was $= 0.05$; if the probability did not stay at $\alpha = 0.10$, the parameter was dropped from the analysis.

Analysis of variance followed by Tukey's test (Steele and Torrie, 1960) was used to test if the parameters which were entered in the discriminant analysis differed significantly among groups in a univariate sense. In order to estimate an unbiased error rate, 15 randomly selected impoundments were not used in the discriminant analysis to develop the discriminant functions and classification coefficients. These 15 impoundments were later classified using the discriminant analysis results and were used to estimate the error rate.

## RESULTS

Polar ordination of non-standardized data of the 27 water quality parameters defined three groups of impoundments (Fig. 2). The ISODATA cluster analysis defined two groups. Both methods of defining groups of impoundments were similar, in that group 1 from the polar ordination contained the same impoundments as group 1 from the cluster analysis. The difference was that ordination further defined a third group from the remaining impoundments. The results from the polar ordination were selected for further analyses. No clear groupings by the type of impoundment or area from which the sites were selected were discernable. Group 1 contained mostly ponds from Colony with a livestock and coal surface mine impoundments, one from Sheridan and one from Firesteel. Group 2 contained five livestock ponds, coal surface mine impoundments from Sheridan and Beulah, and only one bentonite surface mine impoundment. Group 3 was made up of surface mine impoundments from all the locations and two livestock ponds.

The results of discriminant analysis indicated a high degree of separation among the three groups of impoundments estimated by polar ordination. Two cannonical discriminant functions were estimated using three of the 27 variable (Table 1). Both functions accounted for a significant amount of variation among the groups (85% and 66%, respectively). Together, these variables accounted for a total of 93% of the variation in the data. The first function was primarily driven by silica content, and the second function contrasted specific conductivity with chlorine (standardized coefficients in Table 1). Inspection of Fig. 3 suggests that the first function separated group 1 impoundments from groups 2 and 3, whereas, the second function separated impoundments from group 2 and group 3.

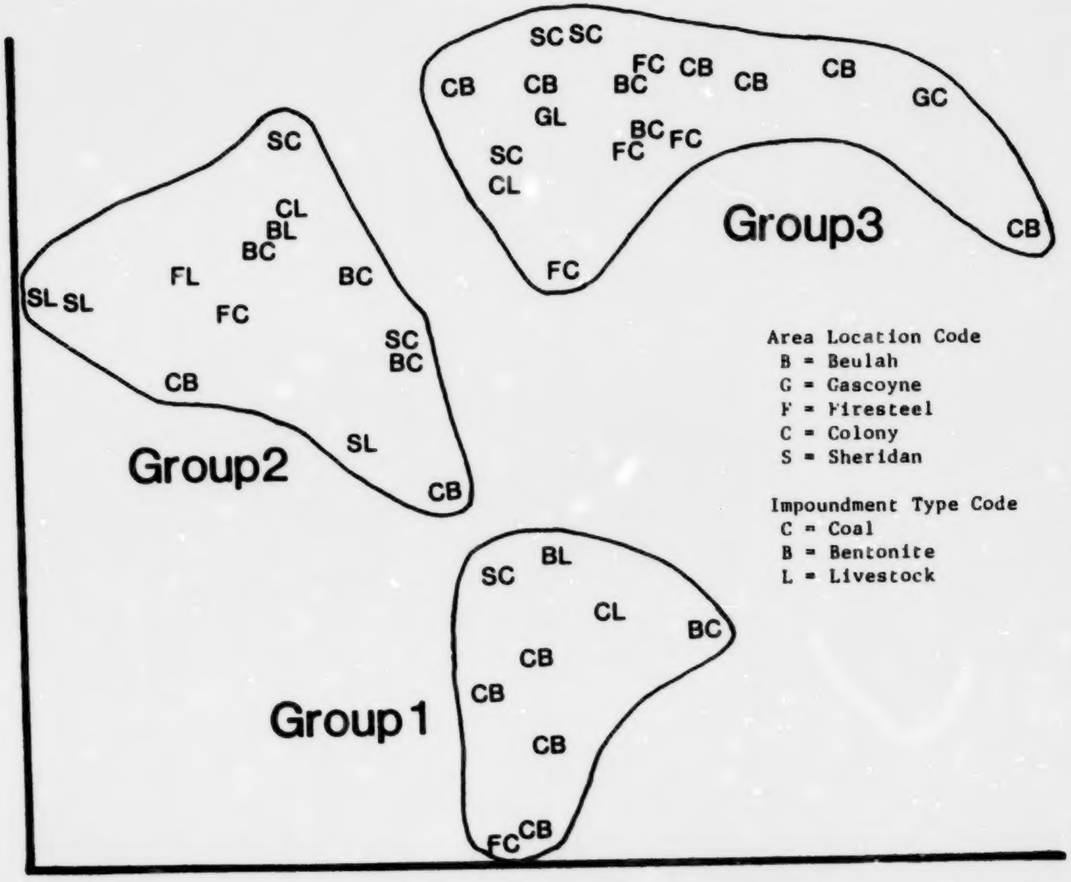

Fig. 2. Impoundment groups from polar ordination.

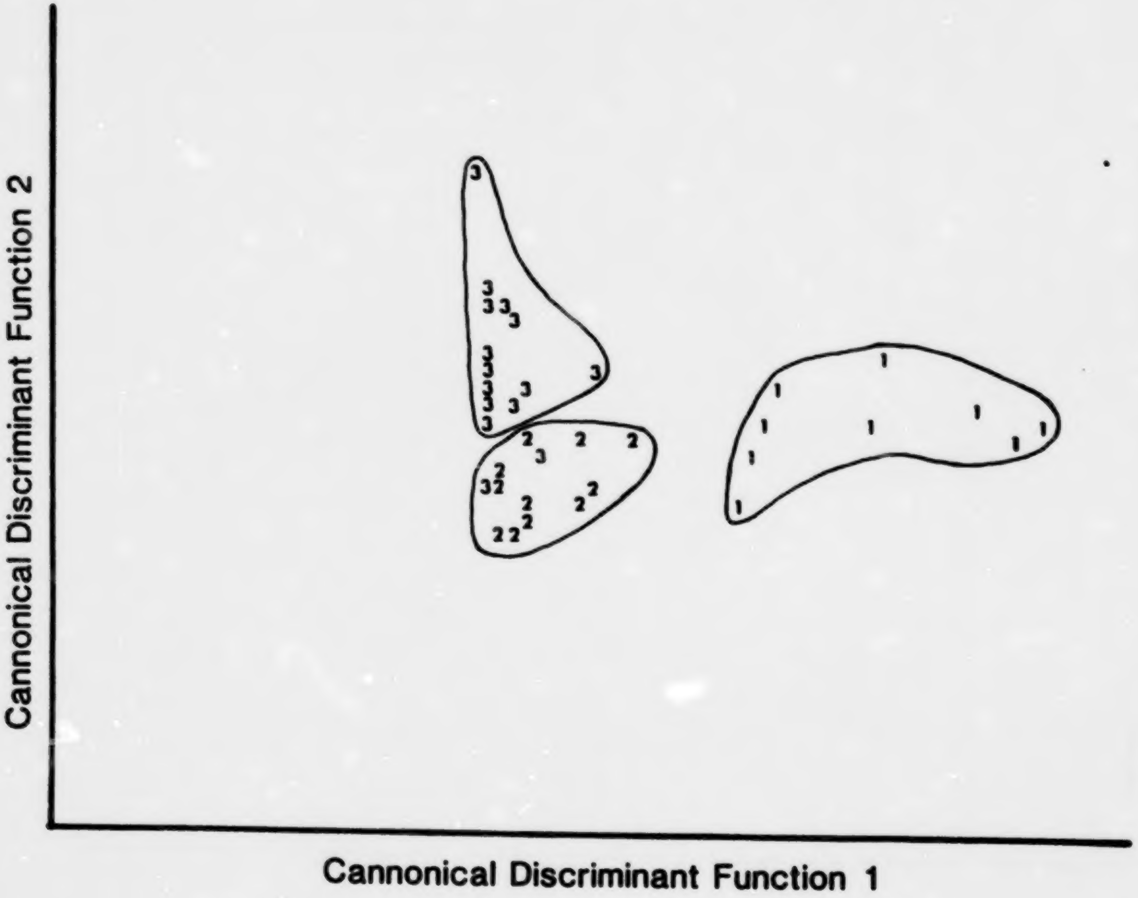

Fig. 3. Plot of water impoundments from discriminant functions derived.

Table 1. Water quality parameters for classifying man-made water impoundments on the northern Great Plains from stepwise forward-backward discriminant analysis.[1]

| Water quality parameter | Standardized canonical[2] discriminant coefficients | | Total % variation explained |
|---|---|---|---|
| | Function 1 | Function 2 | |
| Silica | 1.00 | 0.13 | 85 |
| Specific conductivity | -0.20 | 3.89 | 89 |
| Chlorine | 0.19 | -3.42 | 93 |

[1] Variables are listed in order of entrance into the discriminant analysis.

[2] Absolute value indicates relative importance in the function derived.

Analysis of variance of the variables entered in the discriminant analysis provide additional information specific to each variable (Table 2). The analysis of silica indicated a separation between impoundments from group 1 and those from group 2 and 3, similar to the first cannonical discriminant function. Chlorine and specific conductivity indicated a separation between groups 2 and 3, similar to the second discriminant function.

Table 2. Results of analysis of variance for water quality parameters entered into the stepwise forward-backward discriminant analysis by impoundment group.

| | Group 1 | N | Group 2 | N | Group 3 | N | Sig. |
|---|---|---|---|---|---|---|---|
| Parameters | $\bar{x}$(SE)[1] | 9 | $\bar{x}$(SE) | 14 | $\bar{x}$(SE) | 18 | level |
| Silica[2] | 13.1(1.4)$^{a}$ | | 1.6(0.4)$^{b}$ | | 1.0(0.2)$^{b}$ | | <0.01 |
| S. C.[3] | 1427.8(197.4$^{a}$ | | 939.3(108.5)$^{a}$ | | 3766.7(596.4)$^{b}$ | | <0.01 |
| Chlorine | 8.8(2.1)$^{a\ b}$ | | 6.9(1.3)$^{a}$ | | 27.3(8.1)$^{b}$ | | 0.04 |

[1] Means with the same letter superscript for water quality parameter are not different from each other ($p \leqq 0.05$) as determined by Tukey's test.

[2] Silica, and chlorine were measured in mg/l; specific conductivity in mhos/cm.

[3] S. C. = Specific Conductivity.

Classification functions were estimated for each group (Table 3). Applying these functions to the original data resulted in 92% (two of 26 were misclassified) correct classification of impoundments, showing good internal reliability. Classification of the impoundments withheld resulted in 93% (14 of 15) correct classification or an estimated error rater of 7-8%.

Table 3. Classification coefficients for man-made water impoundments on the northern Great Plains.

| Parameter | Coefficients for<br>Group 1 | Group 2 | Group 3 |
|---|---|---|---|
| Silica | 0.0029 | 0.0004 | 0.0003 |
| Specific conductivity | 0.0044 | 0.0019 | 0.0062 |
| Chlorine | -0.2866 | -0.1262 | -0.4092 |
| Constant | -24.4624 | -1.9907 | -6.5246 |

## DISCUSSION AND CONCLUSIONS

Polar ordination and cluster analysis were both used as a check to place a degree of confidence on the groupings estimated. If these procedures provided entirely different groupings, the results would have been suspect. The groupings estimated by the polar ordination were selected because the later discriminant analyses were able to do a better job of separating three groups than for two groups. Inspection of how the cannonical discriminant functions separated groups suggested that the first cannonical discriminant function defined the same relationship among groups as did the cluster analysis. The second discriminant function separated groups 2 and 3 as defined by the ordination procedure. The significance level of the second function gives confidence that three groups rather than two existed.

The results of the discriminant analysis were reinforced by the analysis of variance which provided univariate insight into where differences existed among impoundment groups. The variables determined to be important in discriminating between the groups of impoundments were significantly different among groups in the analyses of variance. Whereas there were eight other parameters which were different among the three groups, the three variables which resulted from the discriminant analysis were better able to separate the groups of impoundments defined. If the results of discriminant analysis departed widely from the analyses of variance, this would indicate a high degree of variable interactions.

The results of this study indicate that artificial impoundments were quantitatively classified with 93% reliability, based on measurements from three parameters (silica, specific conductivity, and chlorine). The method for classification involves taking the measurements for each of the three parameters and multiplying the values obtained by the coefficients applicable to each parameter which were estimated by the classification functions for each group. These are then summed, and the group with the highest score is the group to which the particular impoundment is assigned. The same procedure can be used to monitor changes in the status or classification of an impoundment resulting from management activities. This procedure, while correct, can result in some loss of information resulting from the holding back of a portion of the data. Another procedure has been recommended which uses a jack knifing procedure (Lackenbruch and Mickey, 1968). This procedure is better unless data are not limiting, and is available on some computer packages (e.g. BMDP7M).

For this type of classification to be useful to managers, the groups determined must have biological or other logical interpretations placed on them. The procedures tested in this study separated the impoundments based primarily on silica, specific conductivity and chlorine content. There were other characteristics associated with each of the groups of impoundment. However, they were more variable relative to the groups of impoundments than the parameters which resulted from these analyses or they would have been selected. For example, group 3 impoundments had high concentrations of potassium, sodium and sulphate. Safe tolerance levels of sulphates for livestock consumption are about 2,500 mg/l (Digesti and Weeth, 1976). Average concentration of sulphate in group 3 impoundments was 2,156 mg/l; the highest concentration of sulfate was 9,100 mg/l. Therefore, some impoundments classified in this group may contain higher than acceptable levels of sulphur for livestock drinking water. The average specific conductivity from group 3 impoundments would be considered a very high salinity hazard for use as irrigation water (Richards et al., 1954). These are two of many of the types of interpretations that need to be made for the application of this type of classification to field situations.

Some caution should be addressed in using this type of approach to classifying habitats. In some cases, the classification may be changed, depending on the objectives of the classification. By omission, the types of variables measured can also dictate the results of this type of classification. These results are not an all-inclusive classification scheme. Other parameters would need to be measured. In other situations, the categories or groups may be determined by other means such as stratification based on production of fish or even the type of impoundment (livestock, bentonite or coal). Regardless of how the groupings are derived, discriminant analysis may be used to place a degree of confidence on the classification and estimate an error rate based on quantitative measurements of a limited number of parameters. In situations where multivariate data analyses are used, high correlations do not necessarily imply cause and effect relationships. Therefore, care should be taken to assess which parameters have ecological relevance to the study area. The indicators of the habitats or groups may be artifacts of the data set; careful interpretation of results will help to identify these situations.

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# PRAIRIE POND MORPHOMETRY AND AQUATIC PLANT ZONATION - NORTHERN HIGH PLAINS

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## ABSTRACT

Before U. S. Public Law 95-87, surface mine and livestock ponds on the northern High Plains had uniquely different physical features. Surface mine ponds varying in age from 12 to 25 years for bentonite clay and coal, respectively, had smaller surface areas, greater water depths, and steeper basin slopes than livestock ponds. Livestock ponds were richer than surface mine ponds, floristically , with 106 plant species compared to 76 on surface mine ponds.

## INTRODUCTION

Approximately 260,000 livestock ponds were constructed in North Dakota, South Dakota, eastern Wyoming and eastern Montana by 1964 (Bue et al., 1964). The number of livestock ponds has increased yearly since 1964, representing a significant aspect of rangeland ecosystems. There were only a few multiple-use management plans for these rangeland ecosystems despite potential benefits such as improved wildlife habitat, irrigation, water sources for livestock, and various recreational activities.

Surface mine ponds, formed when mine pits fill with underground water, precipitation, and runoff, are increasing in numbers on the northern High Plains as a result of greater demand for alternate energy sources. It is estimated that energy demand will increase to 159 quadrillion Btu's by A.D.2000 (U.S. Bureau of Mines 1971). Fifty-seven percent of the lignite and 98 percent of the subituminous coal reserves of the United States are in North Dakota, Wyoming, and Montana, making the northern High Plains a prime target for future mining (Averitt, 1973). Demands for bentonite clay are projected to more than double by A.D. 2000 (Cooper, 1970). As a result of the mining activity, surface mine water impoundments will increase, and resource managers will need to develop multiple-use management plans for these ecosystems.

Wetland plant communities, a major component of prairie pond ecosystems, are closely associated with water regimes created by basin morphometry characteristics. Wetland plants provide key habitat (food sources, escape, nesting, brood rearing, and winter cover) for a variety of wildlife species. More information is available on aquatic plant ecology of natural wetlands (Bell, 1956; Dinsmore, 1958; Riley, 1960) compared with that available for livestock ponds and dugouts (Dane, 1959; Lathwell et al., 1969). Vegetation analysis of livestock ponds and pre-law surface mine ponds of the northern High Plains is very limited. Some information exists on aquatic vegetation and waterfowl use in relation to pond shape and size (Evans and Kerbs, 1977; Lokemoen, 1973; Mack and Flake, 1980; Rumble and Flake, in press).

This paper describes the morphometric features of livestock and pre-law surface mine ponds in relation to associated wetland plant communities.

## METHODS AND PROCEDURES

Study areas were selected to represent the climatic, edaphic, and physiographic variation of surface mine sites on the northern High Plains (Fig. 1). At each site, one livestock pond and one surface mine pond were chosen to represent typical "constructed" water impoundments. All pond construction was done before the 1970s--before most environmental legislation.

Study ponds were selected to be representative of the norm (i.e. water permanence, abundance of wetland vegetation and minimal adjacent disturbance) for coal, bentonite clay and livestock ponds in each area.

### Field Studies

Wetland plant communities were sampled on ponds from early July to late August over a three-year period (1976-1978). Five major transects were placed equidistantly around each study pond, transversing wet meadow, shallow marsh, deep marsh, and open water vegetational zones (Stewart and Kantrud, 1971). Along each major transect, several minor transects 15 m long were placed perpendicularly, passing through the core of each wetland plant community crossed or intersected by the major transect (Mandossian and McIntosh, 1960). Approximately 20-25 randomly-placed 0.25-$m^2$ sampling quadrats were distributed along minor transects, within each major transect, to distribute sampling in the wetland community. In each quadrat, canopy coverage and number of individuals were estimated for each plant species.

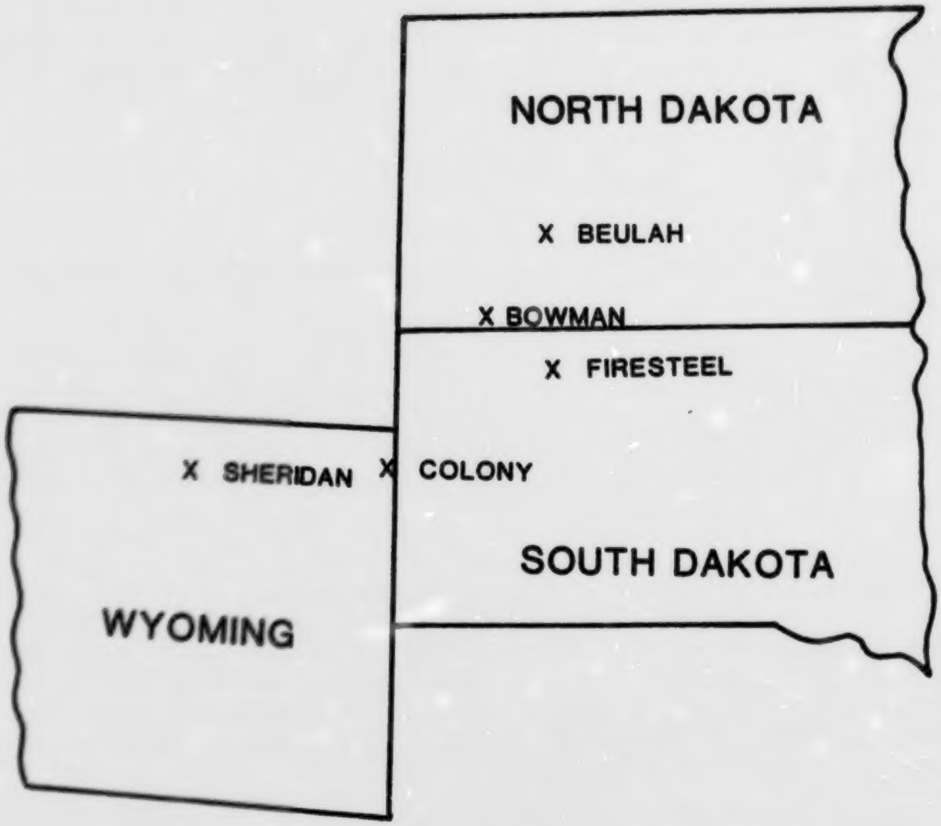

Fig. 1. Location of coal and livestock ponds: bentonite and livestock ponds located at Colony, Wyoming.

Depth of water was measured in each sample quadrat. Soil water was recorded as saturated (depths 0.1-0.9 cm), damp (soil surface wet or depth less than 0.1 cm), or dry. Saturated, damp, and dry quadrats were recorded as 0.5, 0.05, and 0 cm, respectively.

Combined topographic and bathymetric contour maps describing basin morphometry were drawn from field data, using standard techniques and formulas (Welch, 1948). One-way analysis of variance and Tukey's w-procedure were used to statistically analyze differences among pond types (Steel and Torrie, 1960).

## RESULTS AND DISCUSSION

### Physical Characteristics of Pre-law Surface Mine Ponds and Livestock Ponds

Pre-law surface mine and livestock ponds have uniquely different physical features with correspondingly different wetland vegetation patterns. Pre-law surface mine ponds generally have smaller basin surface area, greater maximum water depths, steeper basin slopes, and less shallow water compared to livestock ponds (Table 1).

Basin slope 1 m above and below the water level influences the presence, size, and structure of wet meadow and littoral plant communities. Mean percent slope 1 m above and below the water level is greatest on coal surface mine ponds and least on livestock ponds (Table 1). Bentonite clay and coal surface mine ponds display a significantly smaller percent shallow water area compared to livestock ponds--20.4 and 22.6%, respectively, versus 55.8%.

Steep basin slopes reduce water-saturated shoreline areas capable of supporting wetland vegetation, while gradually sloping substrates, alternately inundated and exposed by fluctuating water levels, provide ideal conditions for wetland plant germination and establishment, rapid plant decomposition, and nutrient cycling (Kadlec, 1962).

Shoreline length, another physical feature estimated by morphometry, is directly related to the amount of area available for wetland plant community establishment. Coal surface mine ponds had the most irregular shorelines, but shoreline development was not significantly different from that of livestock ponds. However, shoreline development must also be considered in terms of basin slope to fully visualize the amount of suitable habitat for plant community development. Uneven water surface expansion on gradually-sloped livestock ponds, resulting in non-linear shorelines, offered considerably more potential for wetland vegetation development.

Table 1. Morphometric data for study ponds. Data expressed are averages, with standard error in parenthesis. Pond types with different superscript letters are significantly different from other types within a column at =0.05 according to Tukey's w-procedure (from Hawkes, Anderson and Rumble In Press.

| Pond type | Number of ponds | Age | Area (ha) | Mean depth (m) | Maximum depth (m) | Shoreline[1] development (ratio) | Mean percent slope | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Above water[2] ($) | Below water[3] ($) | Shallow water[4] ($) |
| Coal | 19 | 24.9 (2.6)$^{a}$ | 1.2 (0.2)$^{a}$ | 2.3 (0.2)$^{a}$ | 4.6 (0.4)$^{a}$ | 2.16 (0.12)$^{a}$ | 60.4 (7.5)$^{a}$ | 35.6 (2.5)$^{a}$ | 22.6 (1.7)$^{a}$ |
| Bentonite | 12 | 11.5 (2.2)$^{b}$ | 2.7 (0.5)$^{b}$ | 0.8 (0.1)$^{b}$ | 6.1 (1.1)$^{b}$ | 1.45 (0.1)$^{b}$ | 24.1 (4.5)$^{b}$ | 17.4 (2.8)$^{b}$ | 20.4 (3.0)$^{a}$ |
| Livestock | 9 | 41.2 (6.2)$^{c}$ | 4.72 (1.7)$^{c}$ | 0.6 (0.1)$^{b}$ | 3.0 (1.0)$^{c}$ | 2.0 (0.2) $^{a}$ | 10.4 (1.3)$^{c}$ | 6.6 (0.7)$^{c}$ | 55.8 (8.1)$^{b}$ |

[1] Ratio of shoreline length of a pond to the circumference of a circle with the same area as the pond.

[2] This slope is for the zone between the water line and the contour line 1 m evaluation above the water line.

[3] This slope is for the zone between the water line and the contour line 1 m evaluation below the water line.

[4] Shallow water is the percent of total pond area represented by the area lying between the water line and the contour line 1 m elevation below the water line.

## Features of Wetland Plant Communities

### Floral composition

The flora on livestock ponds is considerably richer than on pre-law surface mine ponds (Olson, 1979). Seventy-six species, representing 20 families, identified on pre-law surface mine ponds (Table 2), compared with 106 plant species, representing 28 families, on livestock ponds (Table 3). On both surface mine and livestock ponds, the plant families with most representatives included *Poaceae*, *Asteraceae*, and *Cyperaceae*. Numbers of plant species by family on surface mine and livestock ponds were, respectively: *Poaceae*, 14 and 20 species; *Asteraceae*, 14 and 17 species; and *Cyperaceae*, 9 and 14 species.

Plant species were grouped into categories based on habitat preferences and growth forms. Percent composition by category was similar between surface mine and livestock ponds. However, more species occurred in each category on livestock ponds. The number of species and percent of all species (in parentheses) for surface mine and livestock ponds were respectively: wet meadow, 57 (75.0) and 77 (72.6); emergent, 10 (13.2) and 13 (12.3); floating-leaved, 1 (1.3) and 3 (2.8); floating and suspended, 1 (1.3) and 2 (1.9); and submerged, 7 (9.2) and 11 (10.4).

Common species in surface mine ponds were *Eleocharis palustris*, *Typha latifolia*, *Typha X glauca*, *Potamogeton pectinatus*, and *Myriophyllum exalbescens* (Table 2), while livestock ponds included *Hordeum jubatum*, *Eleocharis palustris*, *Typha latifolia*, *Scirpus acutus*, *Potamogeton pectinatus*, and *Myriophyllum exalbescens* (Table 3). *Myriophyllum exalbescens* dominated submergent communities in strip mine ponds, while *Potamogeton* species prevailed in livestock ponds.

### General characteristics

Wetland plant communities on surface mine ponds are arranged in narrow, concentric bands around the pond margin, compared to a large, complex mosaic distribution pattern on livestock ponds. Steep-sloped surface mine basins, coupled with constant water levels, provided a narrow shoreline zone with suitable moisture conditions for wetland plant establishment. In contrast, uneven surface water expansion on gradually-sloped livestock ponds creats more diversified shoreline habitat, encouraging a complex mosaic pattern of wetland plant establishment.

Millar (1969 a,b), Sloan (1970), and Stewart and Kantrud (1971) all describe four concentric zones of natural wetland vegetative development based on water permanence and depth: wet meadow, shallow marsh, deep marsh, and open water. The outermost wet meadow zone is comprised of short, fine textured grasses (such

Table 2. Mean area and percent of basin area for each wetland plant community sampled in pre-law surface mine ponds over a three year period.[1]

| Ponds/Communities (Years community present) | Mean Area ($\text{ha}^2$) | Percent of basin area |
|---|---|---|
| Beulah | | |
| *Phragmites australis* (3) | 0.03 | 1.7 |
| *Typha* X *glauca* (3) | 0.78 | 43.3 |
| *Myriophyllum exalbescens* (2) | 0.22 | 12.2 |
| Open Water | 0.98 | 54.4 |
| Total Basin Area | 1.80 | |
| Bowman | | |
| *Eleocharis palustris* (1) | 0.09 | 2.3 |
| *Scirpus pungens* (1) | 0.05 | 1.3 |
| *Scirpus pungens* - *Eleocharis palustris* (2) | 0.10 | 2.5 |
| *Eleocharis palustris* - *Typha latifolia* (2) | 0.07 | 1.8 |
| *Scirpus acutus* (3) | 0.10 | 2.5 |
| *Potamogeton pectinatus* (1) | 0.15 | 3.8 |
| *Myriophyllum exalbescens* (1) | 0.27 | 6.8 |
| *Potamogeton pectinatus* - *Myriophyllum exalbescens* (2) | 0.56 | 14.0 |
| Mudflat (1) | 0.21 | 5.3 |
| Open Water | 3.33 | 83.2 |
| Total Basin Area | 4.00 | |
| Firesteel | | |
| *Spartina pectinata* (3) | 0.12 | 3.8 |
| *Eleocharis palustris* (1) | 0.02 | 0.6 |
| *Typha latifolia* (2) | 0.11 | 3.5 |
| *Typha* X *glauca* (3) | 0.38 | 12.1 |
| *Scirpus acutus* (1) | <0.01 | 0.3 |
| *Potamogeton pectinatus* (1) | 0.25 | 7.9 |
| *Myriophyllum exalbescens* (2) | 0.33 | 10.5 |
| Mudflat (1) | 0.10 | 3.2 |
| Open water | 2.30 | 73.2 |
| Total Basin Area | 3.14 | |
| Sheridan | | |
| *Typha* X *glauca* - *Typha latifolia* (1) | 0.18 | 9.6 |
| *Typha* X *glauca* (2) | 0.26 | 13.8 |
| *Myriophyllum exalbescens* (2) | 0.43 | 22.9 |
| Open Water | 1.45 | 77.1 |
| Total Basin Area | 1.88 | |
| Colony | | |
| *Hordeum jubatum* (1) | 0.03 | 1.9 |
| *Scirpus maritimus* (3) | 0.05 | 3.3 |
| *Scirpus validus* (3) | 0.03 | 1.9 |
| *Typha latifolia* (3) | 0.07 | 4.6 |
| *Typha angustifolia* (3) | 0.03 | 1.9 |
| *Potamogeton pectinatus* (2) | 0.15 | 9.8 |
| Mudflat (1) | 0.04 | 2.6 |
| Open Water | 1.27 | 83.0 |
| Total Basin Area | 1.53 | |

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[1] Indicates community dominants determined by calculating importance value for each species (Curtis and McIntosh 1951).

[2] Total basin area values do not equal area summations for plant communities, mudflats, and open water since unplanimetered tree areas, unvegetated areas, etc. are included within total basin area. Also, open water area includes the area of submerged plant communities. Therefore, percent of basin area values do not total 100.

Table 3. Mean area and percent of basin area for each wetland plant community sampled in livestock ponds over a three year period.[1]

| Ponds/Communities<br>(Years community present) | Mean Area (ha[2]) | Percent of basin area |
|---|---|---|
| Beulah | | |
| *Hordeum jubatum* (3) | 0.85 | 7.3 |
| *Spartina pectinata* (3) | 1.23 | 10.5 |
| *Eleocharis palustris* (3) | 0.18 | 1.5 |
| *Sagittaria cuneata* (1) | 0.01 | 0.1 |
| *Sparganium eurycarpum* (3) | 0.76 | 6.5 |
| *Scirpus fluviatilis* (1) | 0.04 | 0.3 |
| *Scirpus validus* (3) | 0.11 | 0.9 |
| *Scirpus acutus* (3) | 0.42 | 3.6 |
| *Typha latifolia* (3) | 0.40 | 3.4 |
| *Typha* X *glauca* (3) | 0.55 | 4.7 |
| *Potamogeton pectinatus* (2) | 1.16 | 9.9 |
| *Potamogeton richardsonii* (1) | 0.02 | 0.2 |
| *Myriophyllum exalbescens* - *Potamogeton pectinatus* (1) | 0.54 | 4.6 |
| Mudflat (1) | 0.30 | 2.6 |
| Open Water | 6.87 | 58.8 |
| Total Basin Area | 11.69 | |
| Bowman | | |
| *Hordeum jubatum* (3) | 1.13 | 7.6 |
| *Eleocharis palustris* (3) | 0.85 | 5.7 |
| *Scirpus pungens* (3) | 1.15 | 7.7 |
| *Scirpus acutus* (3) | 1.25 | 8.4 |
| *Typha latifolia* (3) | 0.31 | 2.1 |
| *Potamogeton pectinatus* (1) | 1.84 | 12.4 |
| *Potamogeton pectinatus* - *Potamogeton pusillus* (2) | 3.42 | 23.0 |
| Open Water | 10.16 | 68.4 |
| Total Basin Area | 14.85 | |
| Firesteel | | |
| *Hordeum jubatum* (2) | 0.30 | 12.8 |
| *Eleocharis palustris* - *Glyceria grandis* - *Carex lanuginosa* (1) | 0.19 | 8.1 |
| *Glyceria borealis* (2) | 0.41 | 17.4 |
| *Polygonum lapathifolium* (1) | 0.14 | 5.9 |
| *Alisma plantago-aquatica* - *Sagittaria cuneata* (1) | 0.04 | 1.7 |
| *Sparganium eurycarpum* (2) | 0.37 | 15.7 |
| *Scirpus heterochaetus* (2) | 0.04 | 1.7 |
| *Polygonum coccineum* (1) | 0.03 | 1.3 |
| *Potamogeton richardsoni* (1) | 0.21 | 8.9 |
| Mudflat (1) | 0.07 | 3.0 |
| Open Water | 0.76 | 32.3 |
| Total Basin Area | 2.35 | |
| Sheridan | | |
| *Hordeum jubatum* - *Eleocharis acicularis* (1) | 0.03 | 3.4 |
| *Eleocharis palustris* (2) | 0.08 | 9.2 |
| *Sagittaria cuneata* (1) | 0.05 | 5.7 |
| *Typha latifolia* (3) | 0.14 | 16.1 |
| *Typha* X *glauca* (3) | 0.09 | 10.3 |
| *Potamogeton pectinatus* (3) | 0.35 | 40.2 |
| Open Water | 0.46 | 52.9 |
| Total Basin Area | 0.87 | |
| Colony | | |
| *Hordeum jubatum* (3) | 1.96 | 13.3 |
| *Eleocharis palustris* (2) | 1.59 | 10.8 |
| *Eleocharis palustris* - *Juncus torreyi* (1) | 0.24 | 1.6 |
| *Sagittaria cuneata* (1) | 0.21 | 1.4 |
| *Potamogeton vaginatus* (2) | 2.91 | 19.7 |
| *Potamogeton vaginatus* - *Myriophyllum exalbescens* - *Potamogeton pectinatus* (1) | 1.27 | 8.6 |
| Mudflat (1) | 0.50 | 3.4 |
| Open Water | 10.28 | 69.6 |
| Total Basin Area | 14.78 | |

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[1] Indicates community dominants determined by calculating importance value for each species (Curtis and McIntosh 1951).

[2] Total basin area values do not equal area summations for plant communities, mudflats, and open water since unplanimetered tree areas, unvegetated areas, etc. are included within total basin area. Also, open water area includes the area of submerged plant communities. Therefore, percent of basin area values do not total 100.

as *Hordum jubatum*, and *Distichlis stricta*), and grass-like sedges and rushes including *Eleocharis acicularis*. Shallow marsh, the next inner concentric zone with more favorable moisture regime, supports coarser grasses and grass-like plants of intermediate height such as *Phragmites australis*, *Spartina pectinata*, and *Eleocharis palustris*. Deep marsh, located concentrically inside shallow marsh in several centimeters of water, supports tall, coarse emergents such as *Typha* and *Scirpus* species. The open water zone supports submerged plants such as *Potamogeton* species and *Myriophyllum exalbescens*.

Differences in vegetation zones were apparent between surface mine and livestock ponds. Surface mine ponds lacked wet meadow and shallow marsh zones, compared to livestock ponds. With regard to the deep marsh zone, surface mine ponds exhibited extremely narrow bands of emergent vegetation, such as *Typha* and *Scirpus* species, compared to the broad, extensive areas of emergent vegetation on livestock ponds. Finally, submerged plant communities, such as *Potamogeton* and *Myriophyllum exalbescens*, were restricted to narrow, nearshore bands in surface mine ponds, in contrast to extensive development in livestock ponds. Basin slope, combined with fluctuating water levels, are major factors governing wetland vegetation zones in strip mine and livestock ponds. These two factors limit wetland community establishment by influencing water depth and permanence in wet meadow, shallow marsh, and deep marsh zones (Kadlec, 1962).

## SUMMARY AND CONCLUSIONS

1. Pre-law surface mine and livestock ponds on the northern High Plains had different physical features. Surface mine ponds had smaller surface areas, greater water depths, and steeper basin slopes than livestock ponds.

2. Floristically, livestock ponds were richer than surface mine ponds; 76 different plant species, representing 20 families, were identified on surface mine ponds, compared with 106 species representing 28 families on livestock ponds. Families with the greatest number of species on both surface mine and livestock ponds were *Poaceae*, *Asteraceae*, and *Cyperaceae*. *Eleocharis palustris*, *Typha latifolia*, *Typha X glauca*, *Potamogeton pectinatus*, and *Myriophyllum exalbescens* were more commonly found on surface mine ponds compared to *Hordeum jubatum*, *Eleocharis palustris*, *Typha latifolia*, *Scirpus acutus*, *Potamogeton pectinatus*, and *Myriophyllum exalbescens* on livestock ponds.

3. On surface mine ponds, wetland plant communities were distributed in narrow, concentric bands around the pond margin, compared to larger, more complex, mosaic patterns on livestock ponds. Surface mine ponds did not have plant communities in wet meadow or shallow marsh vegetational zones.

4. Establishment and development of wetland plant communities on surface mine and livestock ponds of the northern High Plains is governed by complex, interacting environmental variables. Water regime and basin slope are major factors influencing the expression of wetland plant communities on rangeland impoundments by affecting (1) the area of shoreline exposed under natural summer drawdowns, and (2) water depth and permanence within wetland plant communities.

   Natural resource managers should reclaim rangeland surface mine ponds by contouring surrounding spoil banks to develop more gradual slopes, creating a more suitable habitat for wetland plant communities.

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# ROOTED AQUATIC PLANT REVEGETATION OF STRIP MINE IMPOUNDMENTS IN THE NORTHERN GREAT PLAINS

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## ABSTRACT

Twelve species of emergent aquatic plants were successfully transplanted on shorelines of two abandoned strip mine ponds in western North Dakota. Three planting techniques (pots, plugs, sprigs) compared planting labor to plant injury. A year after planting, survival was highest in pots, followed by plugs and sprigs. Survival decreased with increasing water depth for all techniques and species. Two years after planting, all plots had increased in area by vegetative spreading. Area occupied was influenced by interactions of species, planting technique, initial survival, water depth, slope, soil erosion/deposition, and soil texture.

## INTRODUCTION

Recent reclamation laws have provided for the development of abandoned strip mine ponds and newly-created impoundments for fish and wildlife habitat (Code of Federal Regulations 1981a, 1981b). For these wetlands to be of high quality there must be a rapid establishment of aquatic plants to meet the food and cover requirements of fish and wildlife. Previous studies have shown natural revegetation of mine ponds to be slow due to adverse physical and chemical conditions (Olson 1979, 1981). Consequently, in 1979, a cooperative project between North Dakota State University, the U.S. Forest Service and Consolidation Coal Company was begun to investigate the survival and growth of artificially established emergent aquatic plants on strip mine ponds.

## METHODS, MATERIALS AND STUDY AREAS

Both transplanting and seeding techniques have been used to successfully establish aquatic plants (Martin and Uhler, 1939; McAtee, 1939; Woodhouse, 1979; Lewis and Bunce, 1980). Seeding was often more economical but required seed bed preparation and water level control. Establishment was often low on exposed sites. Transplanting required more labor but success was better under severe conditions. Seeding was rejected for this study due to the presence of steep, narrow shorelines and the impracticality of water level control. Transplanting techniques were chosen that compared planting labor to plant injury. Planting labor increased and plant injury decreased from sprigs (shoots removed, small rhizome with roots) to plugs (shoots intact, medium rhizome with roots) to plants in fiber pots (shoots intact, large rhizome with roots and soil attached).

Two adjacent twelve-year-old ponds (North and South) at the Glenharold Mine, Stanton, North Dakota were selected as planting sites. Twelve locally common species were chosen whose salinity tolerance matched the salinity of the ponds. Pots and plugs were placed in holes and slits in the soil and sprigs were held down with biodegradable mesh netting. For sampling purposes, plants were placed 0.5 m apart (3 per row) with 3 to 5 rows (also 0.5 m apart) per plot, depending on slope. The first row was along the shoreline and the last row in water depths of 40 to 50 cm. Two replications were planted on the North Pond and one was planted on the South Pond. Each replication had 39 plots - three planting techniques for each of the 12 species plus three control plots. Initial plantings were made in June 1979, followed by sampling in August 1979, and June and August 1980 and 1981. Plant survival, shoot numbers, area occupied, water depth, and soil lost or gained was determined within a 0.25 $m^2$ quadrat relocated in the same grid position each sampling time. Additional quadrat positions were added as plants expanded. Statistical analysis was done with programs in the Statistical Analysis System (Helwig and Council, 1979). All significant differences reported below are at the 5% probability level unless otherwise stated.

Soil particle size analysis showed most shoreline soils were in the silty clay class. Deltas had a slightly higher sand content and were clay loams. Soils were dispersive due to high sodium content with cracks, channels, pipe holes, and pipe outlets common. A KCl extraction with phenanthroline indicated the soils were fairly well oxidized near the surface but were reduced below the surface. Mean electrical conductance was 1.7 mmhos and mean pH was 7.9. Slopes of shoreline plots ranged from 5 to 43% with the majority (74%) between 10 and 25%.

Water in both ponds was alkaline (North pH = 9.1, South pH = 8.6) and dominated by sodium, bicarbonate and sulfate ions. Mean summer conductance (umhos/cm at 25°C) was 1900 in the North Pond and 1400 in the South Pond.

## RESULTS

In August 1979, sprig survival (73%) was already significantly lower than plug (88%) or pot (95%) survival. As water levels dropped during July and August some plants originally planted in shallow water (less than 10 cm) died from desiccation. Sprig survival was significantly lower than that of pots and plugs in shallow water and deep water (over 30 cm). By June 1980 survival was significantly different among all techniques (pots 75%, plugs 61%, sprigs 49%) and decreased with increasing water depth for each technique. Mean survival of all plants in water depths over 30 cm (32%) was significantly lower than that of plants in water depths less than 20 cm (70%). Mean survival of pots (80%) and plugs (75%) was significantly greater than that of sprigs (58%) in water depths less than 20 cm. Overall mean survival of the 12 species was as follows: *Typha latifolia* (78%), *Eleocharis palustris* (74%), *Scolochloa festucacea* (72%), *Scirpus acutus* (70%), *Sparganium eurycarpum* (69%), *Scirpus americanus* (65%), *Typha angustifolia* (64%), *Scirpus validus* (61%), *Scirpus fluviatilis* (53%), *Scirpus maritimus* (45%), *Carex atherodes* (39%), and *Alisma plantago-aquatica* (0%).

Of the total 1239 units planted in June 1979, 506 died by June 1980. During the 1980 growing season only 23 additional plants died. As plants spread during 1980, individual units in each plot became indistinguishable.

In late October 1979, an unplanned drawdown of the South Pond occurred when water was pumped out for road watering (dust control). During 1980, the water level in the South Pond remained below the planted pots until fall. In spite of the drawdown, all species survived and began to spread in 1981 when water levels were high again. Only the plots on the North Pond were used to determine growth by the different techniques and species during 1980 and 1981.

Mean area per plot on the North Pond in June 1979 was 3.2 m$^2$ and fell to 1.9 m$^2$ in June 1980 due to plant mortality. As rhizomes elongated and new shoots were produced area increased continuously during the growing seasons of 1980 and 1981. Shoot production and area occupied were influenced by interactions of species, planting technique, survival in June 1980, water depth, slope, soil erosion/deposition, and soil texture. In June 1979, mean area of pots (2.7 m$^2$) was significantly lower than that of plugs (3.5 m$^2$) and sprigs (3.3 m$^2$) since fewer pots were planted due to the greater labor required. Although percent survival of pots was higher than that of plugs and sprigs, the greater original number of plugs planted still resulted in a significantly larger area of plugs (2.3 m$^2$) in June 1980. The greater mortality of sprigs resulted in areas of sprigs (1.7 m$^2$) and pots (1.6 m$^2$) being similar. By August 1981, area of plugs (10.9 m$^2$) was significantly larger than sprigs (7.5 m$^2$) and pots (9.1 m$^2$) were intermediate.

In August 1981, mean area of plots where soil was deposited (11.1 m$^2$) was significantly greater than the mean area of plots where soil was eroded (6.8 m$^2$). Mean area of plots in clay loam soil (13.3 m$^2$) was significantly greater than those in silty clay soil (8.6 m$^2$). Deep marsh species with larger rhizomes (*Scirpus acutus*, *Scirpus validus*, *Scirpus fluviatilis*, and *Sparganium* *eurycarpum*) had a slightly greater mean area (10.8 m$^2$) than shallow marsh species (8.5 m$^2$) with slender rhizomes (*Carex atherodes*, *Eleocharis palustris*, *Scirpus americanus*, *Scirpus maritimus*, and *Scholochloa festucacea*). On clay loam soils deep marsh and shallow marsh species grew equally well (13.6 m$^2$ and 13.1 m$^2$ respectively), but on silty clay soils mean area of deep marsh species (10.2 m$^2$) was significantly greater than of shallow marsh species (7.3 m$^2$). Pots and plugs on clay loam soils had significantly greater areas than those on silty clay soils. Sprig areas were similar on both soil types. Mean area per plot of the different species was as follows: *Sparganium eurycarpum* (15.7 m$^2$), *Scirpus fluviatilis* (14.7 m$^2$), *Scirpus americanus* (12.7 m$^2$), *Eleocharis palustris* (9.8 m$^2$), *Scirpus maritimus* (6.0 m$^2$, *Carex atherodes* (5.1 m$^2$), and *Scirpus validus* (4.8 m$^2$).

*Typha angustifolia* and *T. latifolia* were excluded from the previous analysis due to a large number of shoots that had originated from seeds from transplated and/or natural stands. Seeds of *Scirpus acutus*, *S. validus*, *S. maritimus* and *Alisma plantago-aquatica* also germinated during the study. By the end of the study, a zonation pattern was developing similar to that found in natural wetlands. Shallow marsh species were spreading laterally along the shoreline in shallow water, while deep marsh species were spreading into deep water.

## CONCLUSIONS

Emergent aquatic plants can be successfully transplanted on shorelines of abandoned strip mine ponds. The greater labor required to plant fiber pots was not justified by the only slightly greater survival than plugs. Planting in water depths over 30 cm was not practical due to low survival. Survival and growth of the various species was affected by soil properties and water depth. In the third year after planting, a zonation was developing similar to that in natural wetlands.

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# ASSESSMENT OF INFILTRATION RATES FOR DISTURBED AND UNDISTURBED SITES AT THE ROSEBUD MINE, COLSTRIP, MONTANA

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## ABSTRACT

During the early fall of 1982 and spring of 1983 Western Energy conducted a brief study at the Rosebud Mine using single ring infiltrometers. The primary purpose of the study was to assess relative infiltration rates for mined and unmined sites and within reclaimed areas to evaluate differences between ages of reclamation, topsoil handling techniques, and seed mixes (i.e. introduced versus native species).

A literature review led to the use of 15 cm diameter single ring infiltrometers. At each site infiltrometers were set out and water levels were automatically maintained at 5 cm by means of bottles equipped with vent and feeder tubes. Rainfall simulator tests were run at four sites for comparison.

Comparison criteria consisted of sites 1) seeded with native species in 1977 and 1979, 2) seeded with native species and introduced species, 3) on native range with reclamation, 4) with sandy and silty soils for each of the above comparisons and 5) where ring infiltrometer and rainfall simulator tests were run.

Infiltration rates for reclaimed sites ranged from 1.0 to 53.2 cm/hr with a mean of 8.9 cm/hr. Infiltration rates for undisturbed sites ranged from 0.9 to 30.4 cm/hr with a mean of 8.9 cm/hr.

Comparisons were evaluated using a standard "t" test. Results of the statistical analyses indicated no significant differences between infiltration rates.

## INTRODUCTION

During 1982-83 Western Energy Company evaluated premine and postmine infiltration rates at the Rosebud Mine. With annual precipitation of 39.6 cm, average evapotranspiration rate of 35 cm/yr (Dollhopf et al., 1982) and 103 cm of annual evaporation, a potential soil moisture deficit of almost 100 cm underscores the importance of maintaining infiltration rates after mining.

Western Energy Company at the Rosebud Mine near Colstrip is mining the Rosebud coal seam which is found in the Tongue River member of the Tertiary age Fort Union formation. The Rosebud Coal is approximately 7.3 m thick and is overlain by varying depths (to about 75 m) of overburden material consisting of interbedded shale, siltstone and sandstone.

The Rosebud Mine uses 45 cu m draglines to strip the overburden off the coal which is then mined using coal shovels. Overburden material is cast (or spoiled) by the dragline across the pit. This process results in fairly thorough mixing of the overburden material. Spoil ridges are regraded by means of crawler tractors and covered with subsoil and topsoil. Wherever possible, the subsoil and topsoil are direct-hauled from in front of the pit to the newly regraded areas.

Little has been done toward assessing infiltration rates on mined land in southeastern Montana. Dollhopf et al. (1982) investigated infiltration on several micro-watersheds at the Rosebud Mine. The micro-watersheds in that study were constructed only on reclaimed surfaces and for the purpose of evaluating various surface manipulation techniques. Approximate ranges of infiltration rates determined in that study were from 1 to 15 cm/hr.

The primary purpose of this study was to assess relative infiltration rates for mined and unmined areas, and to evaluate differences in infiltration rates for different ages of reclamation, different methods of topsoil handling, and variation in vegetation. A secondary purpose was to develop a cost-effective, easy-to-use method for measuring infiltration which would also provide statistical validity.

## METHOD SELECTION

The most widely-used methods for determining infiltration are ring infiltrometers and rainfall simulators. Ring infiltrometers are simple, inexpensive, relatively rapid, relatively unaffected by wind, highly portable and require minimal support equipment. The primary disadvantage is that ring infiltrometers overestimate infiltration. A considerable body of literature addresses the relationship of infiltration rates determined by ring infiltrometers to actual infiltration rates. Rainfall simulators provide a better approximation of natural conditions (and, therefore, actual infiltration rates). Sediment yield data can also be obtained at the same time. Disadvantages of rainfall simulators are that they are cumbersome and may be difficult to set up, time-consuming and require extensive support equipment.

The literature led to additional choices between large versus small infiltrometers and single-ring infiltrometers versus double-ring infiltrometers. With large infiltrometers, some of the advantages of ring infiltrometers are lost, namely portability and ease of use. Burgy and Luthin (1956) compared infiltration basins with single-ring infiltrometers. They concluded that six infiltrometers gave average figures within 30% of the true mean, and that there is no significant difference between single and double-ring infiltrometers. Hills (1971) conducted laboratory experiments using a device which approximated a cross-section through an infiltrometer and soil profile and permitted direct observation of the wetted front. The wetted fronts observed in these experiments approximated the spherical wetting fronts shown in Fig. 1 (from Tricker, 1978). These observations were used to develop a graphical correction procedure for lateral flow under ring infiltrometers.

Tricker (1978) published the results of additional work on lateral flow and the relationship between infiltrometer diameter and error of infiltration measurement. This research led to development of a time-dependent relationship between true infiltration and measured infiltration. Fig. 2 (from Tricker, 1978) shows the relationship between cylinder diameters and error of infiltration measurement. For cylinder diameters of 15 cm and larger the error of infiltration measurement does not vary greatly. However, below 15 cm the error increases dramatically.

Based on the need to rapidly evaluate relative rates at many sites at the Rosebud Mine, Western Energy Company decided to use 15 cm single-ring infiltrometers for their portability, small water requirement, and the possibility of doing 10-15 simultaneously. Comparisons of infiltrometer results with rainfall simulator data were planned to evaluate the best correction procedure. The study plan which evolved called for measurements of relative infiltration rates for sandy versus silty loam, direct lift versus stockpiled topsoils, the native seed mixture now being used versus introduced grass mixtures used in the past, and different ages of reclamation. Rainfall simulator data at four of the sites would correlate with the ring infiltrometer data. Sites chosen are shown on Fig. 3 and listed in Table 1.

## SITE SELECTION

Infiltration rates were measured at a total of 18 site locations (nine paired sites) widely distributed throughout premine and postmine areas, covering a variety of site conditions. Four of the nine pairs were located on land that had been mined (Sites 1-6, 11 and 12) and was in various stages of reclamation. The remaining five pairs of sites were located on undisturbed native range (Sites 7-10, and 13-18).

The two sites in each pair were selected on the basis of soil texture (Table 2). In eight of the nine areas chosen (Sites 1-16), the intent was to select a pair of sites that represented extremes in soil texture found in an area; for example, fine-textured, or predominantly clay soil, versus coarse-textured, or predominantly sandy soil. The pair of sites (Sites 17 and 18), in

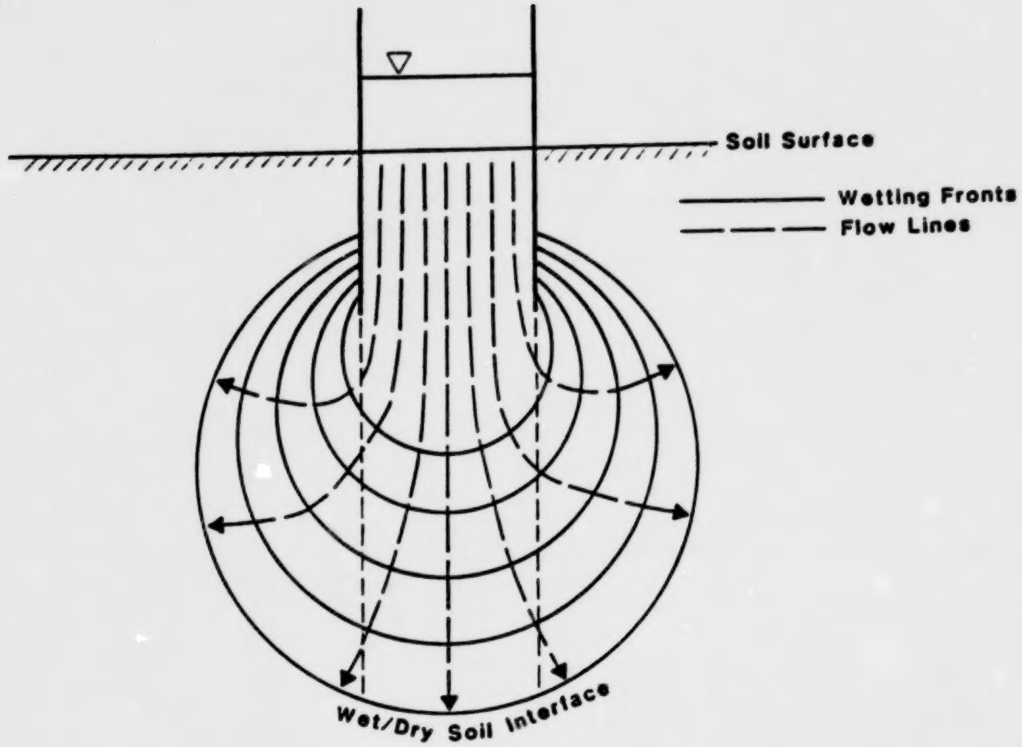

Fig. 1. Water flow b

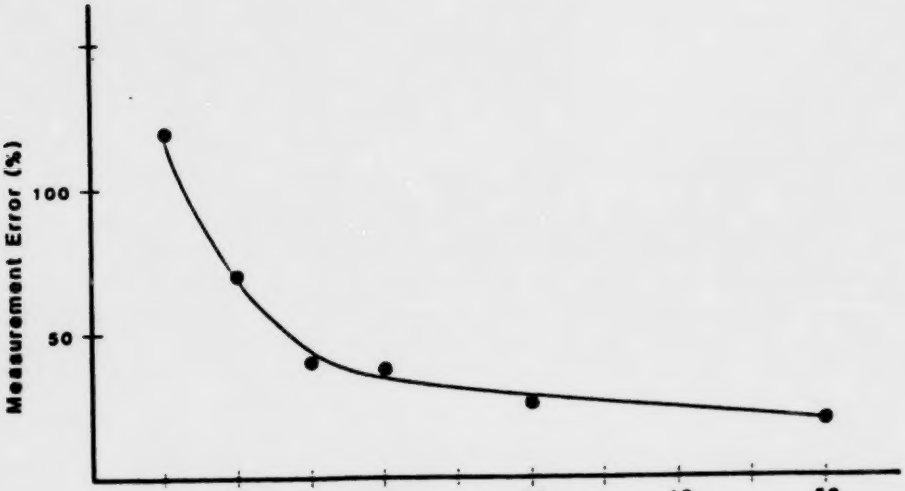

Fig. 2. Relationship between cylinder diameter and error of infiltration measurement.

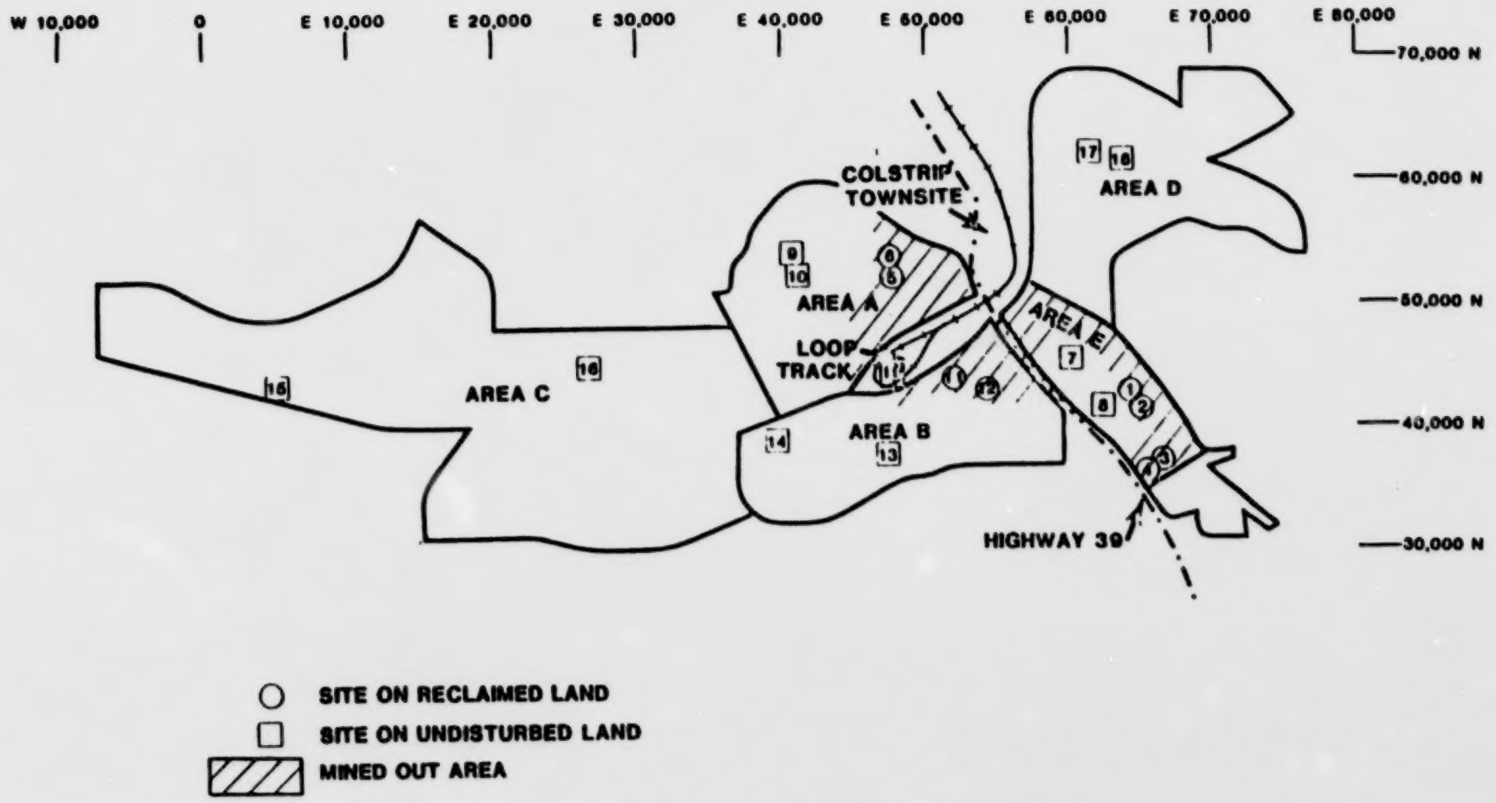

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Fig. 3. Infiltration study site map.

TABLE 1. Infiltration study site locations and descriptions.

| Site | Location | Description | Soil Texture Class | Dominant Vegetation |
|---|---|---|---|---|
| 1 | 46400 N<br>66180 E | Mined Land; Irrigation study plot native seed planted in April, 1979 | Sandy Loam | Thickspike wheatgrass (*Agropyron dasystachyum*)<br>Slender wheatgrass (*Agropyron trachycaulum*)<br>Green needlegrass (*Stipa viridula*) |
| 2 | 46210 N<br>66770 E | Mined Land; Irrigation study plot, native seed planted in June, 1979 | Loamy Sand | Slender wheatgrass (*Agropyron trachycaulum*)<br>Thickspike wheatgrass (*Agropyron dasystachyum*)<br>Sideoats grama (*Bouteloua curtipendula*) |
| 3 | 41550 N<br>67850 E | Mined Land; native seed study plot, comparing seeding methods, mixes, and seeding times, seeded in 1977. | Loam | Western wheatgrass (*Agropyron smithii*)<br>Thickspike wheatgrass (*Agropyron dasystachyum*)<br>Green needlegrass (*Stipa viridula*) |
| 4 | 41410 N<br>67680 E | Mined Land; native seed study plot, comparing seeding methods, mixes and seeding times, seeded in 1977. | Sandy Loam | Western wheatgrass (*Agropyron smithii*)<br>Thickspike wheatgrass (*Agropyron dasystachyum*)<br>Green needlegrass (*Stipa viridula*) |
| 5 | 51820 N<br>51630 E | Mined Land; grazed heavily in 1982, located near fenceline, thus subjected to compaction from cattle. Seeded in 1978. | Loam | Pubescent wheatgrass (*Agropyron trichophorum*)<br>Crested wheatgrass (*Agropyron cristata*)<br>Western wheatgrass (*Agropyron smithii*) |
| 6 | 51910 N<br>51660 E | Mined Land; grazed heavily in 1982, located near fenceline, thus subjected to compaction from cattle. Seeded in 1978. | Sandy Loam | Pubescent wheatgrass (*Agropyron trichophorum*)<br>Crested wheatgrass (*Agropyron cristata*)<br>Western wheatgrass (*Agropyron smithii*) |
| 7 | 47960 N<br>61060 E | Undisturbed land; native range, ungrazed for several years. | Sandy Loam (More sand than Site 8) | Bluebunch wheatgrass (*Agropyron spicatum*)<br>Needle and thread (*Stipa comata*)<br>Prairie junegrass (*Koeleria cristata*) |
| 8 | 45910 N<br>62910 E | Undisturbed land; native range, ungrazed for several years. | Sandy Loam (More clay than Site 7) | Bluebunch wheatgrass (*Agropyron spicatum*)<br>Needle and thread (*Stipa comata*)<br>Prairie junegrass (*Koeleria cristata*) |

| Site | Location | Description | Soil Texture Class | Dominant Vegetation |
|---|---|---|---|---|
| 9 | 51900 N<br>47300 E | Undisturbed land; native range, moderate grazing pressure. | Loam | Bluebunch wheatgrass (*Agropyron spicatum*)<br>Prairie junegrass (*Koeleria cristata*)<br>Western wheatgrass (*Agropyron smithii*) |
| 10 | 50880 N<br>47060 E | Undisturbed land; native range, ungrazed for several years. | Loamy Sand | Bluebunch wheatgrass (*Agropyron spicatum*)<br>Prairie junegrass (*Koeleria cristata*)<br>Western wheatgrass (*Agropyron smithii*) |
| 11 | 46750 N<br>53300 E | Mined land; bare topsoil. | Sandy Loam | No ground cover; seeded immediately prior to infiltration test, with cool and warm season grasses, shrubs and forbs. |
| 12 | 44890 N<br>55150 E | Mined land; bare topsoil. | Loam | No ground cover; seeded immediately prior to infiltration test, with cool and warm season grasses, shrubs and forbs. |
| 13 | 43070 N<br>49180 E | Undisturbed land; native range. | Clay Loam | Western wheatgrass (*Agropyron smithii*)<br>Prairie junegrass (*Koeleria cristata*)<br>Blue grama (*Bouteloua gracilis*) |
| 14 | 41410 N<br>38800 E | Undisturbed land; native range. | Sandy Loam | Bluebunch wheatgrass (*Agropyron spicatum*)<br>Needle and thread (*Stipa comata*)<br>Junegrass (*Koeleria cristata*) |
| 15 | 44480 N<br>4030 E | Undisturbed land; native range. | Clay | Big sagebrush (*Artemisia tridentata*)<br>Bluebunch wheatgrass (*Agropyron spicatum*)<br>Threadleaf sedge (*Carex filifolia*) |
| 16 | 47510 N<br>23500 E | Undisturbed land; native range. | Loamy Sand | Needle and thread (*Stipa comata*)<br>Western wheatgrass (*Agropyron smithii*)<br>Bluebunch wheatgrass (*Agropyron spicatum*) |
| 17 | 64400 N<br>60090 E | Undisturbed land; native range. | Loam | Western wheatgrass (*Agropyron smithii*)<br>Needle and thread (*Stipa comata*)<br>Prairie junegrass (*Koeleria cristata*) |
| 18 | 63690 N<br>64770 E | Undisturbed land; native range. | Sandy Loam | Needle and thread (*Stipa comata*)<br>Western wheatgrass (*Agropyron smithii*)<br>Prairie junegrass (*Koeleria cristata*) |

TABLE 2. Infiltration study site soil textures.

| Site | % Sand | % Silt | % Clay | Texture |
|---|---|---|---|---|
| 1 | 65.7 | 26.6 | 7.7 | Sandy Loam |
| 2 | 77.2 | 16.1 | 6.7 | Loamy Sand |
| 3 | 51.4 | 31.3 | 17.3 | Loam |
| 4 | 52.3 | 32.6 | 15.1 | Sandy Loam |
| 5 | 50.3 | 34.8 | 14.9 | Loam |
| 6 | 65.0 | 24.8 | 10.2 | Sandy Loam |
| 7 | 71.5 | 22.7 | 5.8 | Sandy Loam |
| 8 | 55.2 | 33.1 | 11.7 | Sandy Loam |
| 9 | 46.7 | 41.9 | 11.4 | Loam |
| 10 | 78.9 | 13.8 | 7.3 | Loamy Sand |
| 11 | 73.1 | 18.8 | 8.1 | Sandy Loam |
| 12 | 39.2 | 42.3 | 18.5 | Loam |
| 13 | 20.2 | 50.2 | 29.5 | Clay Loam |
| 14 | 68.4 | 23.4 | 8.2 | Sandy Loam |
| 15 | 14.7 | 31.7 | 53.6 | Clay |
| 16 | 80.0 | 16.2 | 3.8 | Loamy Sand |
| 17 | 50.0 | 28.9 | 21.1 | Loam |
| 18 | 57.3 | 30.6 | 12.1 | Sandy Loam |

the last area chosen were located on mid-range, or loamy-textured soil for the sake of comparison.

The soil texture of each site was initially determined by hand-texturing in the field. Soil samples were later sent to a laboratory for a more accurate textural analysis (see Table 2). Site conditions varied considerably, and are described in Table 1.

## EQUIPMENT

Infiltrometers consisted of thin wall steel pipe, 15 cm in diameter and 25 cm long. Water was supplied to cylinders by means of 3.8 l (1 gallon) glass bottles calibrated in cm of infiltration for 15 cm cylinders. A constant head in each cylinder was achieved by means of two-holed rubber stoppers with a 20 cm length of copper tubing for a vent pipe and a 23 cm length for a feed tube, as shown in Fig. 4. Water was released from the inverted bottle into the cylinder until the ends of both tubes were covered. When the water level in the infiltrometer dropped below the end of the vent tube, air entered the bottle and water was released into the cylinder until the end of the vent tube was again immersed, cutting off the flow of air. By positioning the bottles at the proper height, a constant head of approximately 5 cm was maintained in each cylinder. The bottles were supported by means of boards with three holes separated by approximately 45 cm.

## PROCEDURE

When the equipment was set up, the individual bottles were inverted at 10-second intervals. At observation times, water levels were read at the same 10-second intervals. In this manner, one observer could invert the bottles and read the infiltration directly from the bottles after 5, 10, 15 and 20 minutes and thereafter at 20-minute intervals until a linear relationship between infiltration and time was exhibited (see Fig. 5 for representative plots). Spare bottles were kept on hand for infiltrometer which required more than 3.8 l. For most sites an elapsed time of 80 minutes proved sufficient to define a straight line on the plots.

## RESULTS

The infiltration rate in cm/hr in each cylinder was determined from the slope of the best-fitted line through the plotted points (Fig. 5). Infiltration rates at the Rosebud Mine did not exhibit the time-dependence reported by researchers in other areas. Considerable variation can be seen in infiltration rates presented in Table 3. The validity of some of the comparisons is questionable because of circumstances which were not recognized prior to choosing the locations or which could not be controlled. Comparisons which include Sites 5 and 6 were affected by the

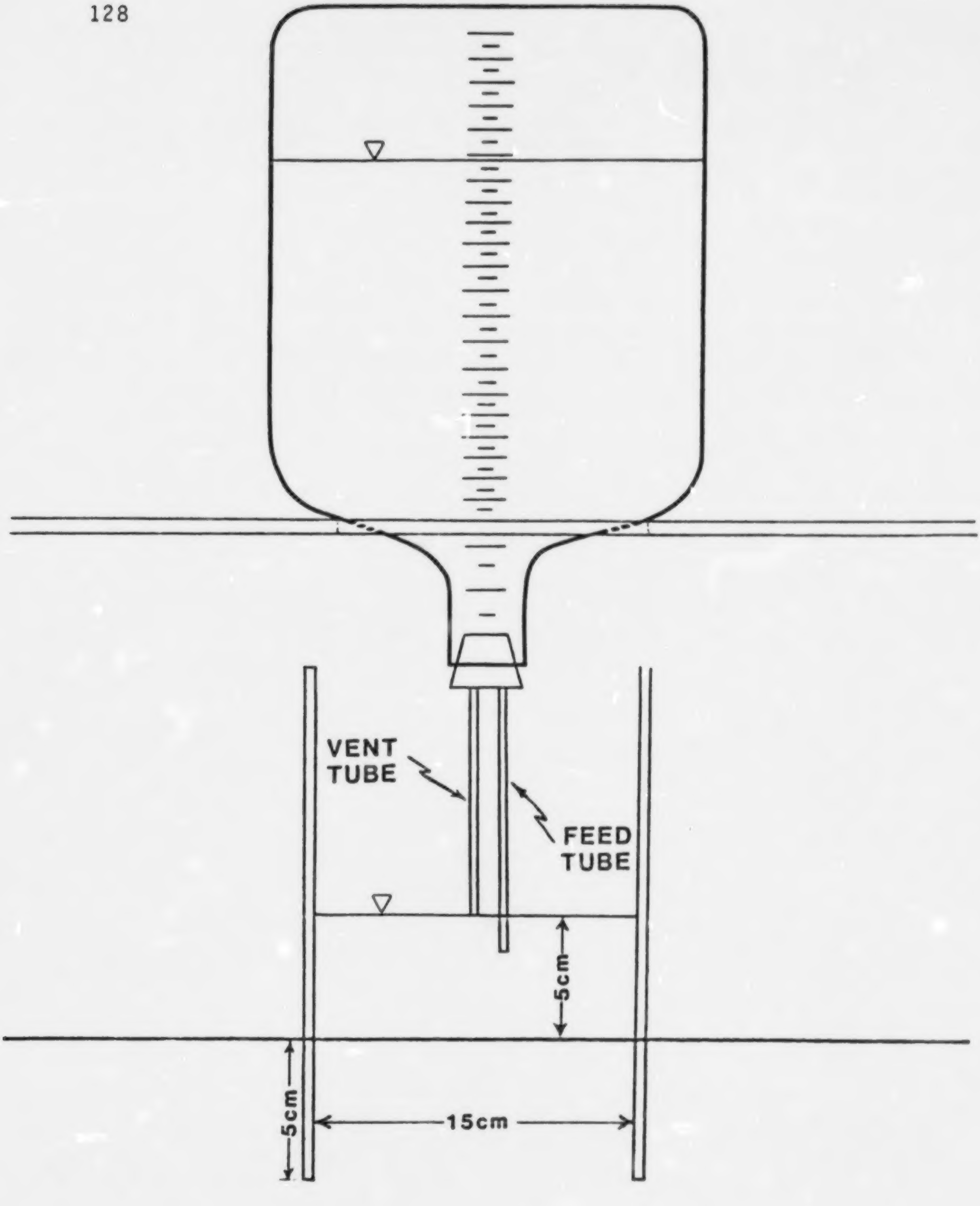

Fig. 4. Infiltrometer schematic.

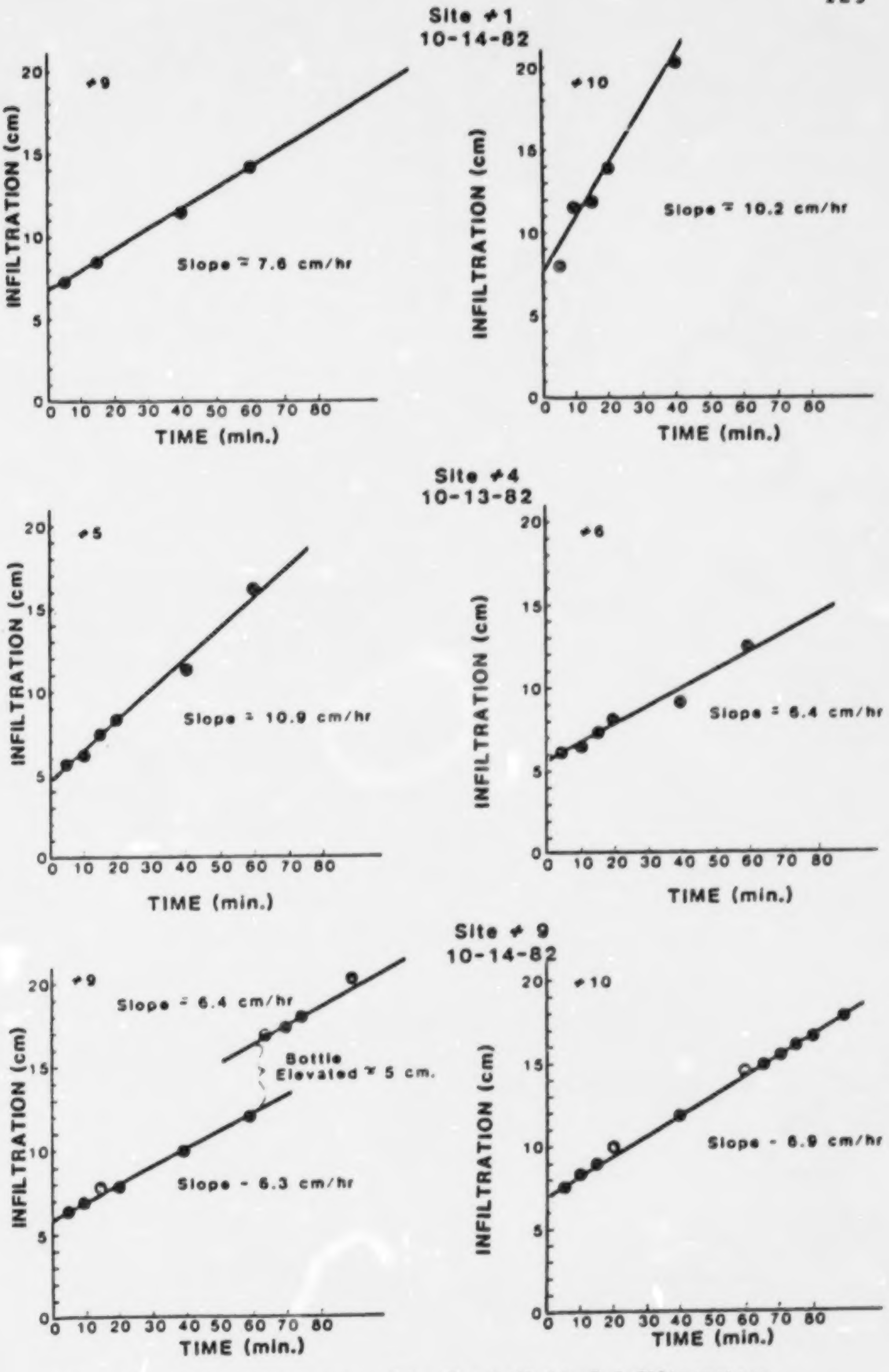

Fig. 5. Representative data plots for individual infiltrometers.

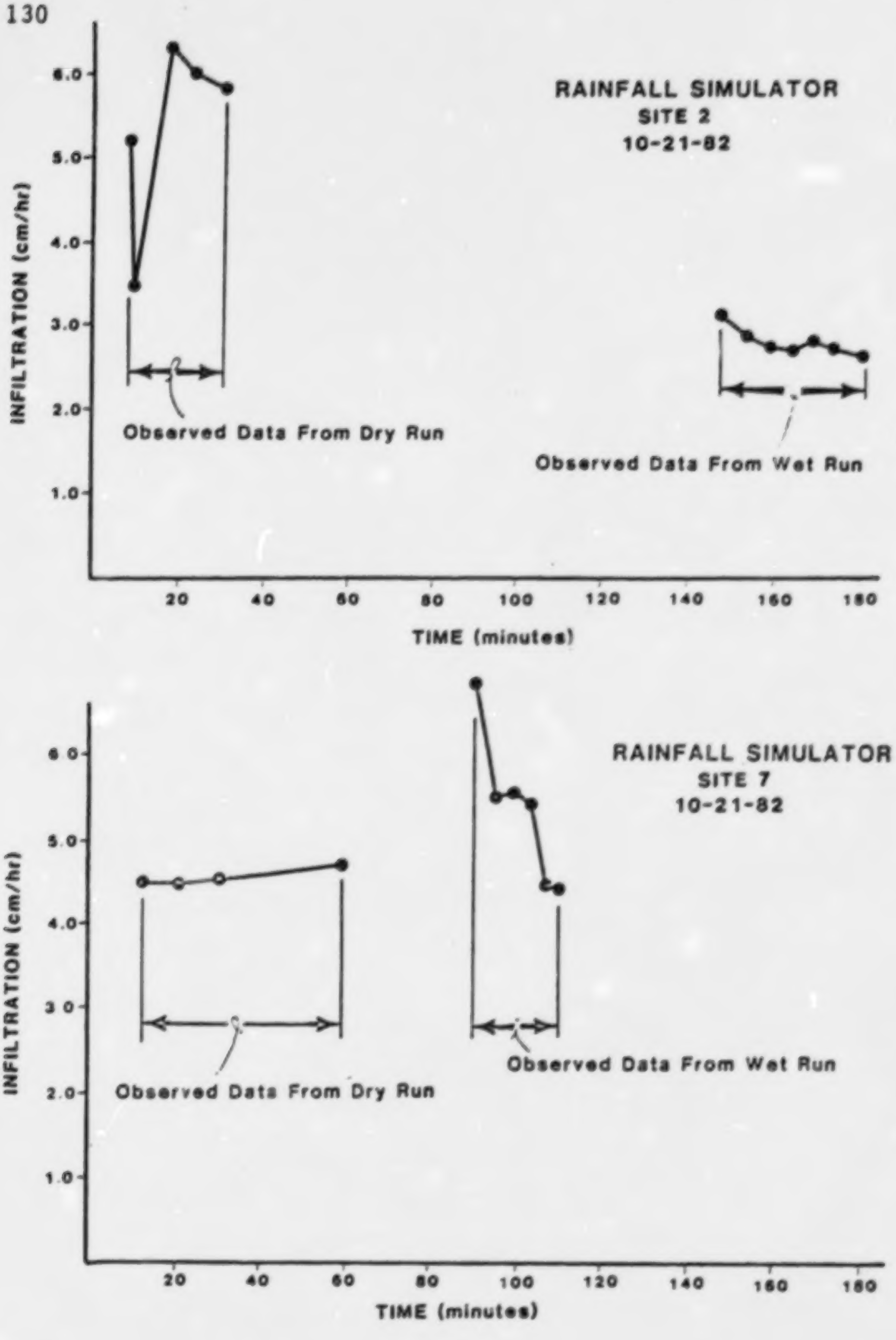

Fig. 6. Rainfall simulator field data.

Table 3. Infiltration rates (cm/hr)

| Site # | Texture | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Average |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | SL (R) | 22.4 | * | 53.2 | 11.0 | 19.6 | 13.4 | 12.1 | 11.7 | 7.6 | 10.2 | 24.0 | 14.0 | 18.1 |
| 2 | LS (R) | 5.9 | 9.5 | 10.0 | 9.3 | 11.0 | 6.0 | 34.5 | 35.5 | 42.5 | 26.0 | 21.5 | 29.0 | 20.1 |
| 3 | L (R) | 10.8 | 28.0 | 14.8 | 4.6 | 8.8 | 9.3 | 3.2 | 9.7 | 6.2 | 6.2 | 11.4 | 24.0 | 11.4 |
| 4 | SL (R) | 9.2 | 3.4 | 2.6 | 7.8 | 10.9 | 6.4 | 20.0 | 11.1 | 15.6 | 11.6 | 7.6 | 2.4 | 9.0 |
| 5 | L (R) | 4.7 | 4.4 | 2.8 | 1.0 | 1.0 | 1.9 | 2.1 | 1.1 | 2.4 | 3.9 | 1.0 | 1.0 | 2.3 |
| 6 | SL (R) | 6.6 | 5.3 | 12.6 | 7.4 | 5.0 | 4.9 | 9.1 | 9.3 | 4.8 | 4.0 | 14.5 | 11.7 | 7.9 |
| 7 | SL (U) | 14.0 | 12.0 | 17.0 | 14.0 | 7.5 | 22.0 | 10.0 | 10.0 | 21.5 | 18.0 | 10.5 | 6.0 | 13.5 |
| 8 | SL (U) | 12.7 | 5.9 | 12.6 | 1.1 | 2.3 | 1.2 | 14.4 | 2.8 | 4.1 | 1.0 | 1.7 | 9.6 | 5.8 |
| 9 | L (U) | 2.7 | 1.4 | 1.2 | 1.0 | 0.9 | 1.6 | 2.1 | 1.3 | 6.3 | 6.9 | * | 1.9 | 2.5 |
| 10 | SL (U) | * | 10.4 | 6.2 | 17.2 | 18.0 | 20.0 | 13.7 | 13.0 | 20.9 | 16.6 | 9.9 | 11.6 | 14.3 |
| 11 | SL (R) | 7.8 | 11.2 | 9.4 | 14.2 | 7.5 | 10.9 | 6.8 | 7.3 | 16.0 | 4.4 | 9.0 | 7.4 | 9.3 |
| 12 | L (R) | 5.4 | 5.2 | 1.9 | 2.6 | 4.4 | 2.9 | 7.4 | 5.0 | 2.9 | 5.4 | 4.9 | 1.9 | 4.2 |
| 13 | CL (U) | 2.7 | 2.3 | 4.4 | 3.0 | 3.0 | 3.6 | 2.1 | 0.9 | 2.0 | 3.0 | 7.1 | 3.3 | 3.1 |
| 14 | SL (U) | 15.0 | 7.6 | 7.9 | 9.4 | 6.7 | 9.1 | 9.8 | 9.3 | 13.2 | 10.2 | 10.8 | 6.0 | 9.6 |
| 15 | C (U) | 2.3 | 1.7 | 2.1 | 1.3 | 2.6 | 1.4 | 3.5 | 2.0 | 1.4 | 4.3 | 2.7 | 1.9 | 2.3 |
| 16 | LS (U) | 26.8 | 26.0 | 26.8 | 24.4 | 21.2 | 22.0 | 26.4 | 23.6 | 30.4 | 23.2 | 22.4 | 29.2 | 25.2 |
| 17 | L (U) | 4.4 | 4.3 | 7.2 | 4.0 | 5.0 | 12.6 | 8.5 | 10.6 | 2.1 | 4.4 | 6.8 | 6.3 | 6.4 |
| 18 | SL (U) | 9.6 | 9.5 | 6.8 | 8.1 | 8.7 | 4.4 | 4.6 | 5.2 | 5.4 | 8.1 | 6.3 | 6.8 | 7.0 |

Texture Abbreviations: S = Sand, L = Loam, C = Clay, U = Undisturbed, R = Reclaimed, * = No Determination

## Table 4. Infiltration study comparisons

| Comparison | Sites | Average Infil. Rate (Ring) CM/HR | Sites | Average Infil. Rate (Rain) CM/HR |
|---|---|---|---|---|
| Soil Type | | | | |
| Silty | 1,3,5,8,9,12,13,15,17 | 6.1 | 5,9 | 1.1 |
| Sandy | 2,4,6,7,10,11,14,16,18 | 12.9 | 2,7 | 5.3 |
| Seed Mix | | | | |
| Native | 1,2,3,4,11,12 | 11.9 | 2 | 5.9 |
| Introduced | 5,6 | 5.1 | 5 | 1.0 |
| Age of Reclamation | | | | |
| 1977 | 3,4 | 10.2 | | |
| 1978 | 5,6 | 5.1 | 5 | 1.0 |
| 1979 | 1,2 | 19.1 | 2 | 5.9 |
| *1982 | 11,12 | 6.7 | | |
| Direct Hauled vs. Stockpile Topsoils | | | | |
| Direct Haul | 1,2 | 19.1 | 2 | 5.9 |
| Stockpile | 5,6 | 5.1 | 5 | 1.0 |
| Reclaimed vs. Undisturbed | | | | |
| Reclaimed | 1,2,3,4,5,6,11,12 | 10.2 | 2,5 | 3.5 |
| Undisturbed | 7,8,9,10,13,14,15,16,17,18 | 9.1 | 7,9 | 3.0 |

*Seeded Day of Test

## Table 5. Rainfall simulator infiltration data

| Site | Soil/Vegetative Condition | | Dry | Wet |
|---|---|---|---|---|
| 2 | Native Seed 1979 | Application Rate | 3.1 in/hr | 1.4 in/hr |
| | Loamy Sand Topsoil | Application Time | 30 min | 60 min |
| | | Initial Infiltration | 5.2 cm/hr | 3.3 cm/hr |
| | | Final Infiltration | 5.9 cm/hr | 2.8 cm/hr |
| 5 | Introduced Seed (1978) | Application Rate | 3.1 in/hr | 1.4 in/hr |
| | | Application Time | 31 min | 30 min |
| | Loam Topsoil | Initial Infiltration | 0.7 cm/hr | 1.3 in/hr |
| | Surface Crust | Final Infiltration | 1.0 cm/hr | 0.1 cm/hr |
| 7 | Native Range | Application Rate | 2.0 in/hr | 3.1 in/hr |
| | Sandy Loam Topsoil | Application Time | 60 min | 30 min |
| | | Initial Infiltration | 4.5 cm/hr | 6.9 cm/hr |
| | | Final Infiltration | 4.7 cm/hr | 4.5 cm/hr |
| 9 | Native Range | Application Rate | 3.1 in/hr | 1.4 in/hr |
| | Loam Topsoil | Application Time | 20 min | 22 min |
| | | Initial Infiltration | 6.3 cm/hr | 2.7 cm/hr |
| | | Final Infiltration | 1.2 cm/hr | 1.7 cm/hr |

location of those sites near fence lines where cattle tend to congregate in a field that was heavily grazed during the spring. Vegetative cover and type could not be matched precisely between soil types at some sites.

Comparisons with the highest reliability were soil type and reclaimed versus undisturbed sites. The least reliable comparison was the age of reclamation because of the factors mentioned above. Control sites (sites for which only one variable changes) were not available for some of the comparisons. Comparisons in Table 4 were evaluated statistically by means of "t" tests at a significance level of 0.05. Infiltration rates for 95 determinations at eight reclaimed sites ranged from 1.0 to 53.2 cm/hr with a mean of 10.2 cm/hr. Infiltration rates for 118 determinations at 10 undisturbed sites ranged from 0.9 to 30.4 cm/hr with a mean of 8.9 cm/hr (Table 3). There was found to be no significant difference for any of the comparisons. At Site 9, two rows of bottles were elevated approximately 5 cm in order to evaluate the effect of variations in head of water in the cylinders. Infiltrometer No. 9 from Site 9 (Fig. 5) illustrates typical data from this evaluation. Infiltration rates did not vary for water depths between 5 and 10 cm.

Rainfall simulator tests were conducted by a consulting firm using a simulator based on a design developed by the United States Department of Agricultural Sedimentation Laboratory (Mayer and Harmon, 1979). The design utilized oscillating spray nozzles directed downward to provide an overlapping pattern on 1.5 by 5 m rainfall plots bounded by metal edging. Runoff was measured by means of an overland flow catchment tray and graduated collection bucket. Infiltration was calculated as the difference between rainfall and runoff. Typical data plots are shown on Fig. 6. Rainfall simulator infiltration data are summarized in Table 5. Infiltration rates calculated from the dry runs show a consistent and logical variation with ring infiltrometer data (Fig. 7). Infiltration rates calculated from the wet runs do not, possibly due to minor equipment problems, time period between the dry and wet runs too short and antecedent moisture conditions which were not determined prior to the rainfall simulator test. During the three weeks prior to the rainfall simulator runs, 1.1 cm of precipitation had occurred. Since this happened in October when evapotranspiration rates are low, soil moisture conditions during the dry runs may actually have been more representative of conditions desired for wet runs. Only data from the dry runs were evaluated in the statistical comparisons with infiltrometer data. Infiltration rates were 5.9 and 1.0 cm/hr for reclaimed sites and 4.7 and 1.2 cm/hr for undisturbed sites (Table 5). For both the reclaimed and undisturbed sites there was no significant difference between the infiltrometer and rainfall simulator data at the 0.05 level of significance with 2 degrees of freedom.

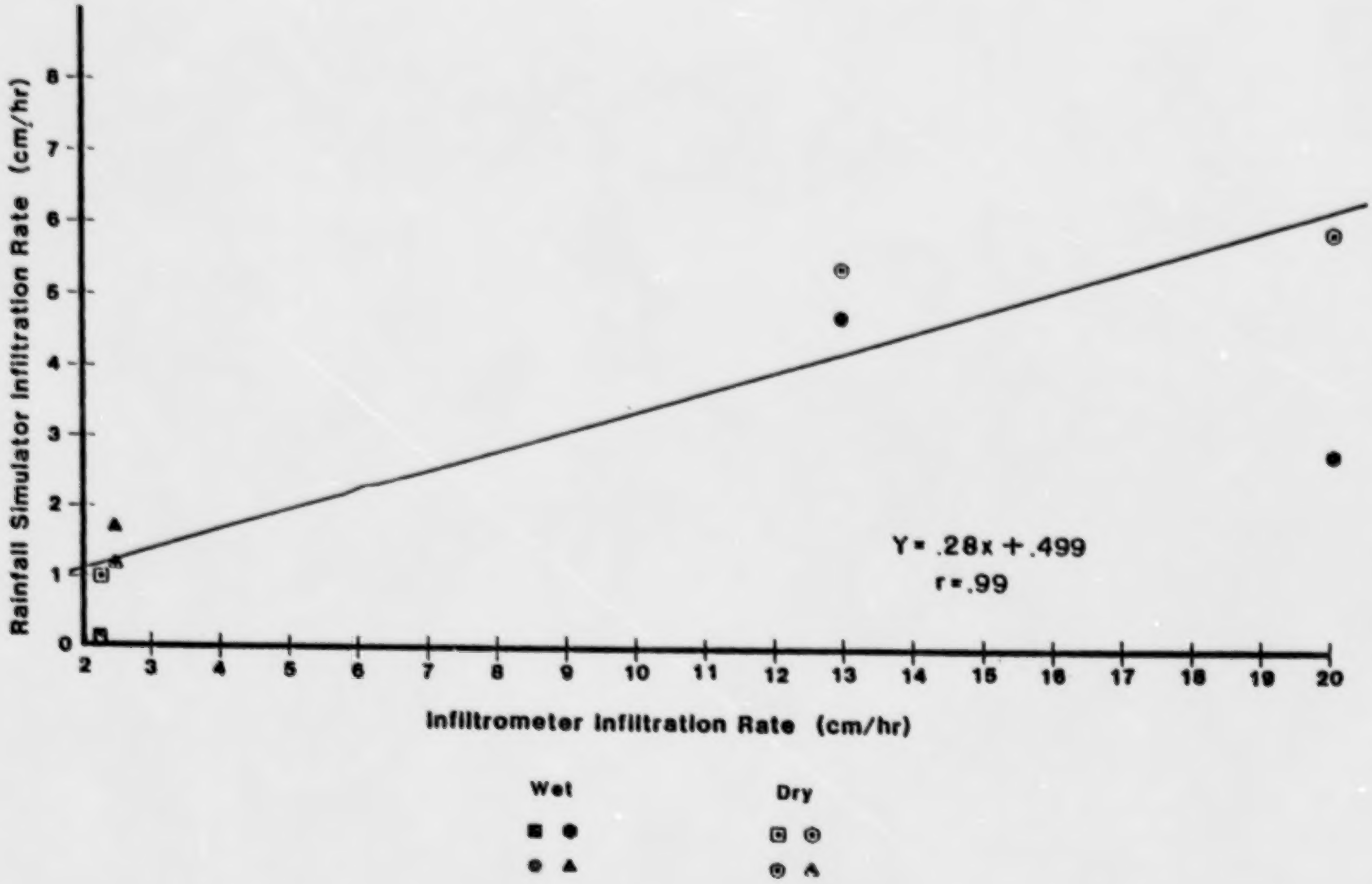

Fig. 7. Relationship between infiltration rates from ring infiltrometer and rainfall simulator data.

## SUMMARY

During October, 1982, and April, 1983, Western Energy Company assessed reclaimed versus undisturbed areas, different ages of reclamation, areas seeded with native species versus areas seeded with introduced species, and direct hauled versus stockpiled topsoils. The study, also meant to assess a method for rapid field determination of infiltration rates, was conducted at 18 sites (1-12 in October, 1982, and 13-18 in April, 1983) using single-ring infiltrometers complemented by rainfall simulator tests at four sites. Results indicate no significant differences beween the infiltration rates on the areas mentioned above. The method evaluated in this study will allow one operator to do 12 or 15 determinations in less than three hours.

Western Energy Company is continuing this research by both measuring infiltration rates at additional sites and also by attempting to determine the actual rate of downward movement of water at four sites. Evaporation pans, precipitation gauges, and neutron probe access tubes or gypsum blocks will be installed at these sites. Infiltration rates have been measured and runoff will be estimated from natural precipitation events by means of catchment buckets which contain the runoff from 1 x 2 m plots isolated by rubber edging. Two sites are on newly reclaimed areas (Sites 11 and 12) and two sites are on unmined areas (Sites 9 and 19). Data from the sources mentioned above will be used to calculate net downward flow and to determine when infiltration and downward movement does occur. These sites will be maintained for a minimum of two years.

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# IMPROVING AQUATIC WILDLIFE HABITAT THROUGH COAL SURFACE MINING IN THE PLAINS

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## ABSTRACT

Wetlands have been steadily drained in the United States over the last two centuries because of their conversion to farmland and urban uses. Surface coal mines do not commonly operate in major wetland regions, yet these mines may be reclaimed as wetland habitat, which can help to reduce the loss rate of this national resource. Four major types of impoundments may be created at a surface coal mine, including: final cut - incline pits; depressions in regraded spoil; sediment settling ponds; and reclaimed slurry ponds. Final cut - incline impoundments are now graded to have side slopes not exceeding 3:1, which has greatly increased the available littoral zone over what was found in such impoundments that were created before passage of U.S. Public Law 95-87, in 1977. If regraded spoil depressions and sediment settling basins have a reliable supply of water, reclamation permits may be obtained to manage these areas as aquatic habitat after the mining finishes. In many cases, slurry ponds may be reclaimed as wetlands by covering acid-bearing zones with earth fill, then establishing suitable aquatic plant communities in the various resulting water depths. Waterfowl and sport fishes are being managed successfully in reclaimed impoundments at a number of Mid-western mines operated by AMAX Coal Company.

The last retreat of the massive Pleistocene glaciers some 25,000 years ago (Eardley, 1965) left North America a legacy of millions of ice-carved depressions which filled with water. Those natural lakes and 'prairie potholes' which occurred in the southern Prairie Provinces and northern Plains States became the most important waterfowl breeding grounds on the Continent (Leitch, 1964; Burwell and Sugden, 1964).

The ice sheets also left another legacy - rich glacial till, which farmers soon recognized as some of the most valuable cropland available. High value of a resource meant high demand for more, so individuals and governments soon determined that by 'reclaiming' shallow lakes with a dragline ditch, more land could be put in production. It has been estimated in the United States that, as of 1977, only 28.5 million hectares of wetlands remained out of the original 51.4 million hectares that existed during colonial times (Studholme and Sterling, 1964; U.S. Soil Conservation Service, 1980). The current drainage rate in the United States is estimated at over 121,400 hectares per year, with the largest part still being in the northcentral states (U.S. Soil Conservation Service, 1980).

The farmer cannot take all of the blame for this drainage, however, since shopping centres, homes and highways have devoured their share of wetlands. Surprisingly, however, the United States surface coal miner's dragline has not been a significant factor in the destruction of wetlands. Through a quirk of nature, the surface-minable coal seams of this country, which were laid down during the Pennsylvanian, Cretaceous and Tertiary Periods, generally occur south or west of the farthest advance by the last ice sheet (compare maps of Eardley, 1965: 415 and U.S. Soil Conservation Service, 1980:18). Eastern mines may cut through small stream or river beds of marginal value for waterfowl production, but even this is generally prohibited west of the 100th meridian, because of the "alluvial valley floor" protections written into the Federal Surface Mining Control and Reclamation Act of 1977 (Public Law 95-87).

Much has been written about mitigating losses of wildlife habitat due to energy development, including coal mining (Swanson, 1979) but, as noted by Klimstra and Nawrot (1982), few have realized that surface coal mining may actually improve or create aquatic wildlife habitat where little existed previously. Strippable coal deposits underlie over 4 million hectares in the United States (U.S. Soil Conservation Service, 1980) and a previous study has shown that a large majority of surface coal mining companies are actively engaged in reclaiming mined land for wildlife habitat (Scott and Zimmerman, In Press). Currently, over 9000 surface and underground mines are operating in the United States (Nielsen, 1982) and each of them controls hundreds, or thousands, of hectares. In the case of creating aquatic habitat for waterfowl where none existed (Christy et al., 1979), some of the millions of hectares to be mined can replace the wetlands lost in the North to drainage. Indeed, previous studies have shown that waterfowl will readily nest in newly-flooded areas outside of their traditional breeding grounds (Kennedy, 1974; Sandusky, 1978; Klimstra and Thornburg, 1982).

In spite of this great potential for creating aquatic habitat at surface coal mines, most biologists (and even some miners) are not aware of the specific types of impoundments that can be developed. The purpose of this paper is to give some examples of where and how water impoundments may be constructed at surface coal mines in the Midwestern plains, along with a history of wildlife management at some representative mine wetlands.

# TYPES OF IMPOUNDMENTS AT SURFACE COAL MINES

## Final Pit and Inclines

Most surface coal mines use a dragline as the major piece of equipment to remove overburden rock (spoil) from the coal seam. The dragline excavates narrow strips (usually 30-50 m wide) that may be 1-4 km long. When the dragline cuts a new strip, it casts the overburden into the previous cut, where the coal has been removed from the bottom. This proceeds throughout the life of the mine, until the final cut is made. Since the mining has stopped, no spoil is available for casting into the final cut. This long, narrow pit can be reclaimed only by hauling material in to fill it (which is rarely done due to the expense) or by grading the sides down, as shown in Fig. 1. Even grading the sides of the final cut pit is very expensive, often costing more than $25,000 per hectare. This cost rises rapidly as final graded slopes become flatter and is always much more expensive than grading the typical mine run spoil banks (Scott, 1981).

Because of this cost, companies generally would prefer to grade the spoils less (leaving steeper banks), and allow the remaining pit to fill with water. State and federal laws require that exposed coal seams or acid-bearing spoil in the final cut must be covered with at least 1.2m (4 ft) of non-toxic material, so the water quality in the final pond will be suitable for fish, wildlife and recreation. The steepness of the banks in these ponds, while suitable for fish and recreational use, may be steeper than desirable for the establishment of aquatic vegetation, which is used as food and cover by waterfowl and furbearers. These plants generally grow best in shallow water, at depths of a few cm to 1 m (Fassett, 1960).

Closely related to the final cut pit in size and shape is the incline, or ramp road pit. Ramp roads are built in the mined spoil, and follow the pit as it advances. The roads are used by trucks hauling the coal up from the bottom of the pit to the coal processing plant, on the normal ground surface. They intersect the mining pit perpendicularly, and rise a vertical distance of 20-50m, at a slope usually not over 6%, to avoid traction problems for the heavily loaded trucks. These roads have high, steep sides, like the final pit, and they are reclaimed in a similar manner, which means that they can form 'arms' to the pond in the final cut pit. The water source for these pits is primarily underground water from the unmined aquifers, but surface runoff also can be diverted into the inclines and final cut.

## Depressions in the regraded spoil

Federal and state laws usually require that most coal mine spoils (excluding final or opening cuts) be graded to a rolling topography with slopes not to exceed 20%. At times, dozers may

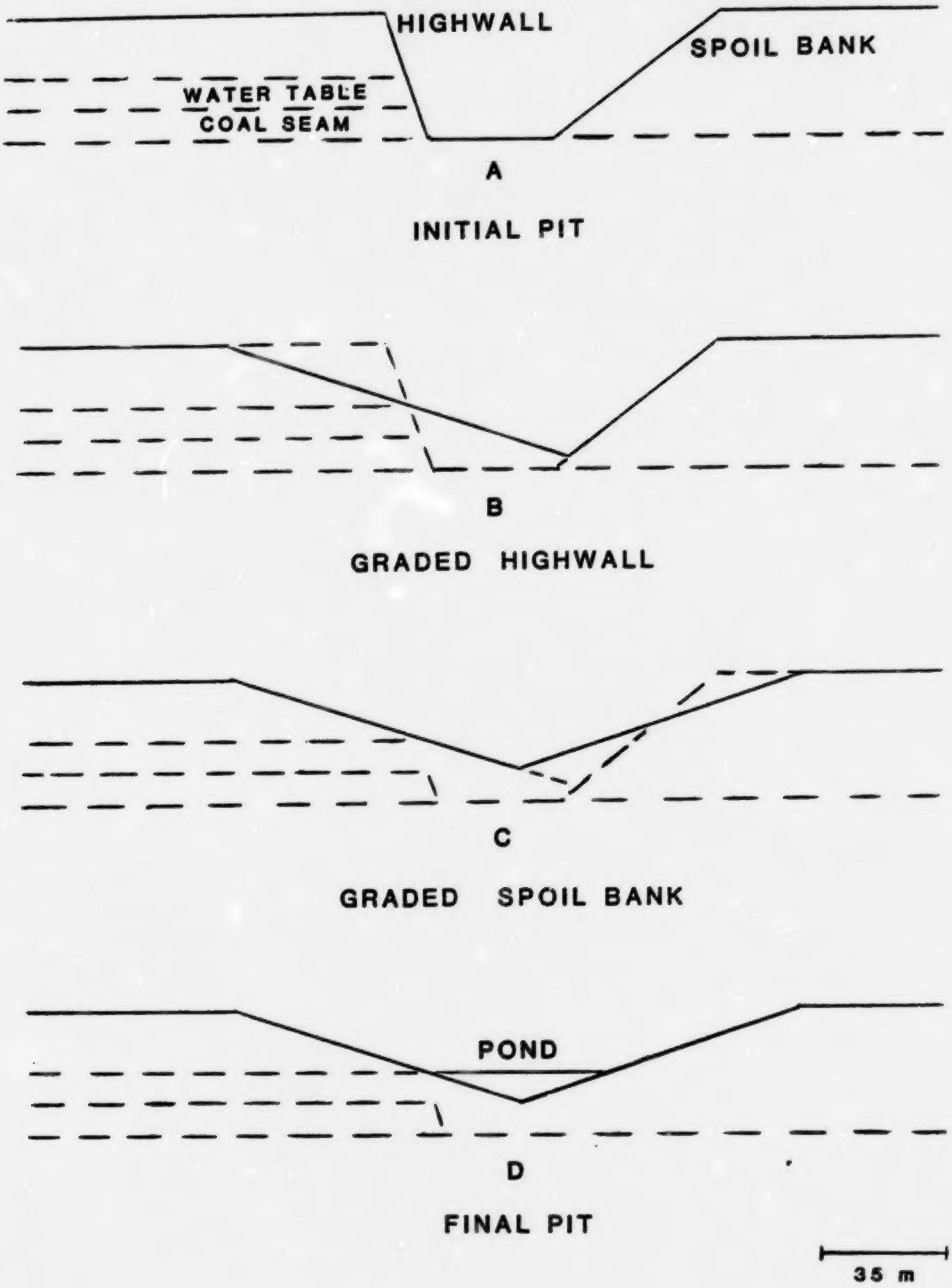

Fig. 1. Cross-sectional views of a typical final cut grading sequence.

create small basins in the graded spoils, and these collect surface runoff. If the water supply is adequate so the basins remain at least partly filled all year, they make ideal shallow ponds for the production of aquatic vegetation and related wildlife.

## Settling Ponds

The Federal Surface Mining Control and Reclamation Act of 1977 requires that surface mines build settling ponds that will trap sediment that may be washed off bare spoil and soil during the mining and reclamation processes. Usually, the law requires that such ponds be removed after thay have served their purpose; however, a company may make a special application to have them retained for fish and wildlife habitat. Some settling ponds are just dammed oxbow channels of a nearby stream, or part of a gulley, while others are excavations created with a dragline, backhoe, or bulldozer. Most are relatively shallow, and offer an excellent opportunity for establishing aquatic plant communities, provided their source of water is adequate to keep them filled year long.

## Reclaimed Slurry Ponds

At many mines, raw coal from the pit must be washed, to remove non-cumbustible small rock particles, before it is sold. The rock and small coal 'fines' are carried away from the coal preparation plant in water, as slurry. The slurry is pumped into an impoundment behind 1-3 m high dikes, where the rock and coal are allowed to settle out. The clear water is then returned to a local stream. After a number of years, the settling capacity of such slurry ponds is reduced, and a new one must be built elsewhere. Sometimes, the mine quits operating before the slurry pond is filled. In either case, most of these ponds are very shallow, but can hold additional water for aquatic vegetation and wildlife, if a local water supply can be diverted through them. Most slurry ponds, however, require special reclamation techniques, because the waste rock and coal they contain often produce sulfuric acid that is toxic to plants and animals.

## SAMPLE IMPOUNDMENTS AT OPERATING MINES IN THE MIDWESTERN U.S.

AMAX Coal Company has seven surface coal mines located in Indiana and Illinois (Fig. 2). Production at Wright Mine terminated in 1982; however, reclamation is currently being completed. During 1982, production for the seven mines totaled 12,204,000 tons. Table 1 provides the 1982 production for each mine and the primary stripping machines utilized. Each of the four types of impoundments were built at all of these mines, except Wright Mine, which did not have a slurry pond. The principal pre-mining land uses at each site were cropland, hay/pasture and forest. A variety of soil types were present at each mine ranging from thin forest soils to the deep, fertile soils of prime farmland areas.

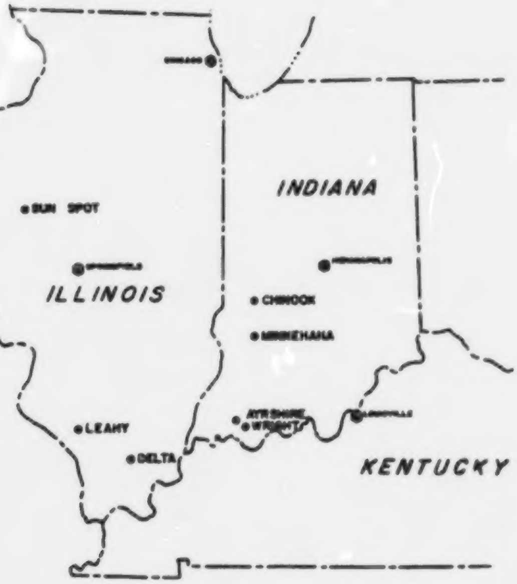

Fig. 2. Location of Midwest surface mines of AMAX Coal Company.

## Final Cut and Incline Impoundments

Final cut and incline impoundments have always been a part of surface mining due to the economic advantages they provide in reclamation. The old (pre-1977) final cut and incline impoundments were characterized by:

- steep side slopes
- little or no littoral zone
- high volume of water:surface area ratio
- in some instances, unsatisfactory water quality.

With the advent of the U.S. Public Law 95-87, the characteristics of final cut and incline impoundments changed significantly. Under present regulations, final cut and incline impoundments are characterized by:

- side slopes which do not exceed 3:1 (horizontal:vertical)
- significantly more littoral zone than the old impoundments
- low volume of water:surface area ratio
- good water quality.

Figure 3 represents a final cut and incline impoundment located at Sun Spot Mine in northern Illinois. Side slopes of the final cut and incline were graded to not exceed 3:1 above the low water line, and soil material was replaced to the low water line. The configuration is typical of final cut and incline impoundments produced by surface coal mines.

Table 1. AMAX Coal Company surface coal mines located in Indiana and Illinois.

| Mine | 1982 Production (Tons)[1] | Primary Stripping Machine (Bucket Capacity)[1] | Year Operation Initiated |
|---|---|---|---|
| Chinook | 1,305,340 | B-E 2570-W Dragline (110 Cu. Yds.)<br>B-E 2550-W Dragline (82.5 Cu. Yds.) | 1928 |
| Minnehaha | 1,338,657 | B-E 2550 Dragline (75 Cu. Yds.)<br>B-E 1250 Dragline (29 Cu. Yds.) | 1953 |
| Ayrshire | 3,406,383 | Marion 8950 Dragline (150 Cu. Yds.)<br>B-E 3270-W Dragline (176 Cu. Yds.) | 1973 |
| Wright | 770,356 | Marion 5761 Shovel (65 Cu. Yds.) | 1954 |
| Sun Spot | 917,011 | Marion 5761 Shovel (65 Cu. Yds.)<br>Marion 8750 Dragline (110 Cu. Yds.) | 1962 |
| Delta | 1,915,385 | B-E 3270-W Dragline (176 Cu. Yds.)<br>Marion 8750 Dragline (110 Cu. Yds.)<br>B-E 1450-W Dragline (60 Cu. Yds.) | 1934 |
| Leahy | 2,551,350 | Marion 7500 Dragline (14 Cu. Yds.)<br>Marion 5900 Shovel (105 Cu Yds.) | 1971 |

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[1] Mining production and bucket sizes are in English units, which are used by the U.S. mining industry.

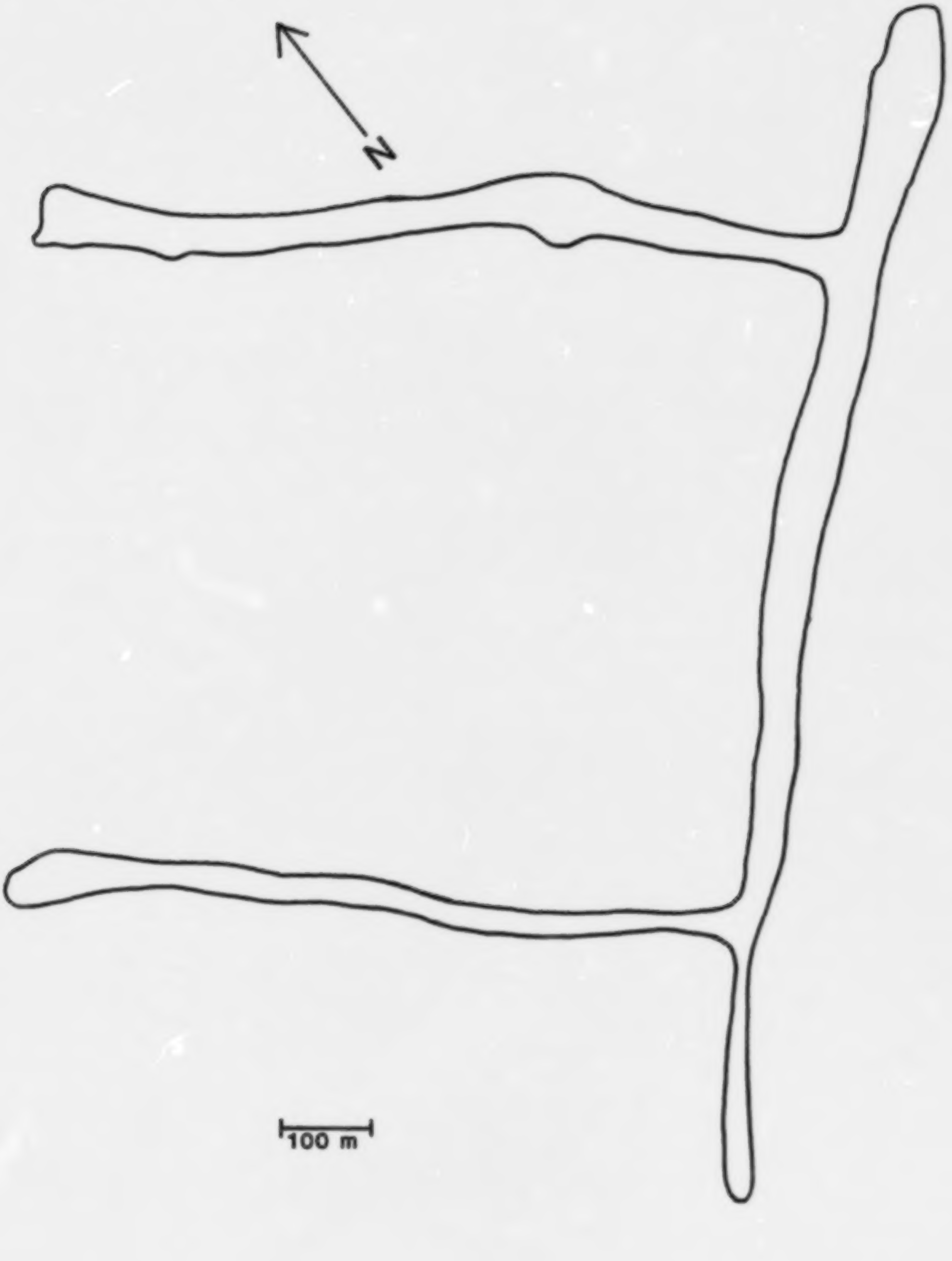


Fig. 3. Final cut-incline pond at the Sun Spot Mine.

Water quality is consistently good in these impoundments due to the quality of reclamation required today in the surrounding area. Toxic materials such as pyrite, with its high acid-producing potential, must be buried to prevent acid runoff and, therefore, acidification of the impoundment. Minor amounts of acid-producing materials inundated by the impoundment do not contribute significantly to acid production. Even though some inundated materials may have a high acid-producing potential, the diffusion rate of oxygen in water is so slow that no significant amount of acid generation can occur (Pionke and Rogowski, 1979).

### Depressions in the Spoil

Depressions in the spoil are acceptable in reclamation when they are specified and planned for in the mining permit, and when they contain water of sufficient quantity and quality to meet the requirements of the intended use. Uses which commonly justify such impoundments include recreation, sport fishing, and livestock watering. Shallow depressions which may become dry during the year are seldom considered acceptable.

Figure 4 illustrates an impoundment created by a depression in the spoil at Ayrshire Mine. Side slopes on depression impoundments are graded so as not to exceed 3:1, and soil material is replaced to the low water line. There is no typical shape for an impoundment created by a depression in the spoil. The configuration is a result of the topography and the grading. Depressions in the spoil have a high potential for vegetative diversity.

### Settling Basins

Settling basins are designed to retain sediment carried in surface runoff. Being designed for this specific purpose, they are in most instances removed during reclamation, since there often is not an adequate supply of water to satisfy traditionally accepted uses. Settling ponds can, by law, be retained only when they are constructed with excess storage capacity. Only in those instances where topography can be used to advantage is excess capacity economically feasible. In these instances, the resulting impoundment resembles the typical farm pond, as illustrated in Fig. 5, and is commonly located on unmined land on the perimeter of the disturbed area. Settling basins retained as permanent impoundments enhance the diversity of the water resources available on surface mined areas.

### Slurry Ponds

Slurry ponds are traditionally viewed as a serious environmental liability and existing regulations require they be covered with 1.2 m (4 ft) of non-toxic material. AMAX Coal Company is working with Southern Illinois University to demonstrate slurry

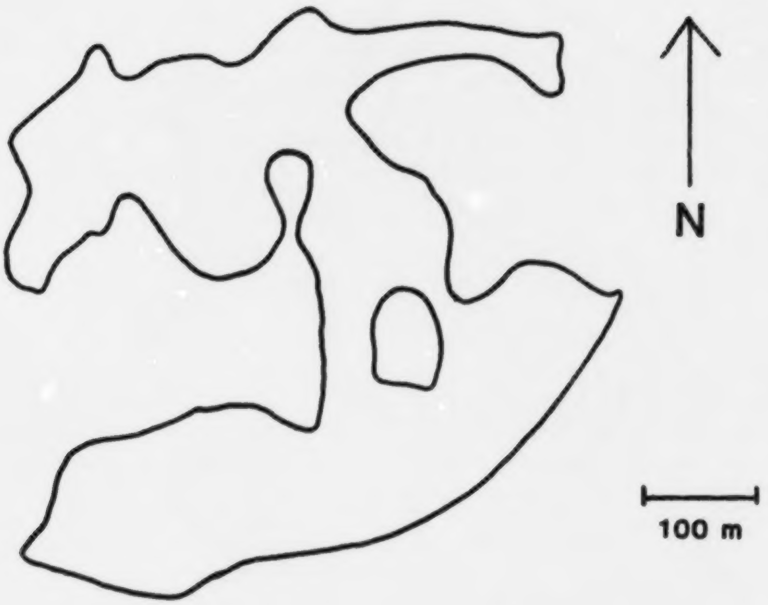


Fig. 4. Pond in regraded spoil depression at the Ayrshire Mine.

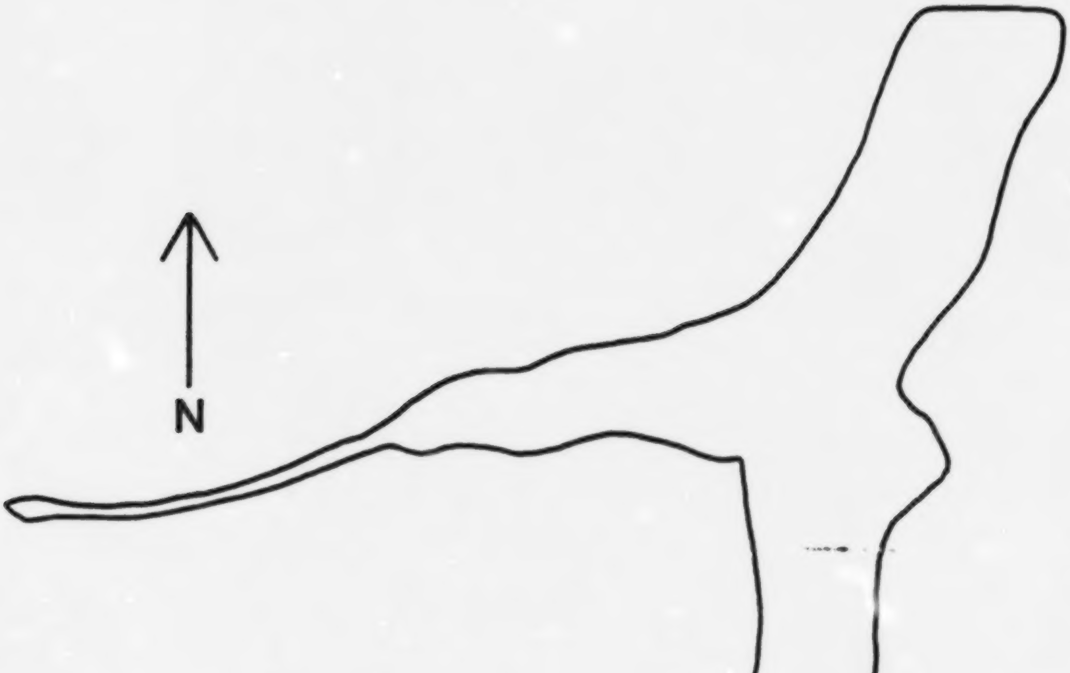
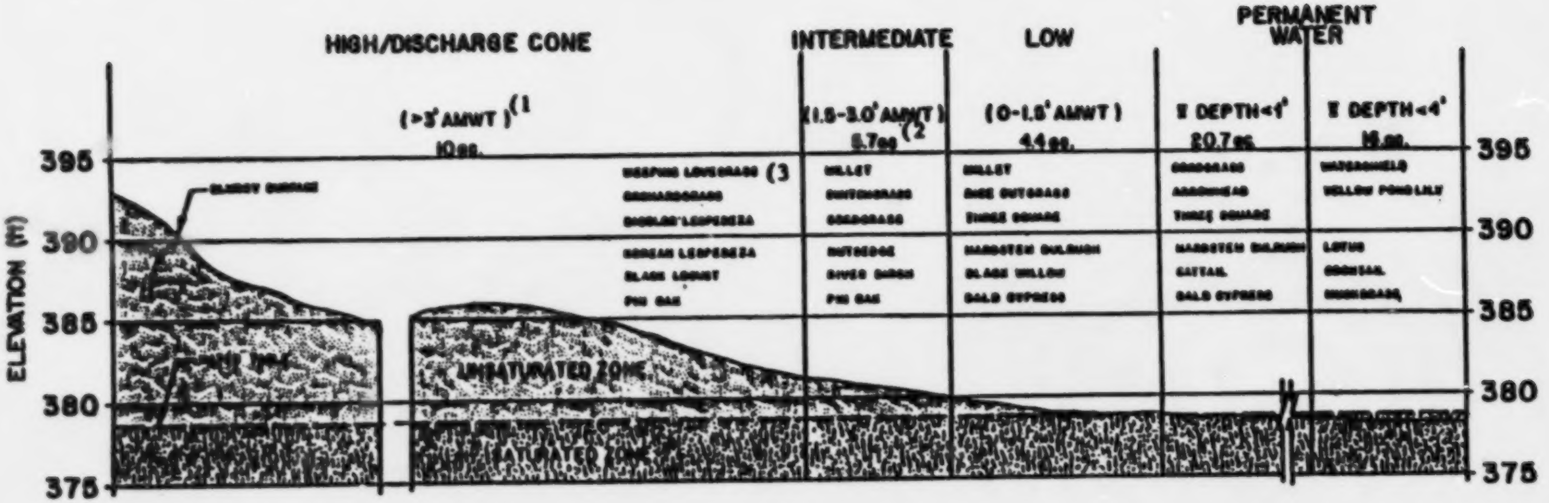


Fig. 5. Settling basin pond at the Sun Spot Mine.



(1 AMWT = Above mean water table.
(2 English units, as used by coal companies.
(3 Plant common names from Fassett (1960).

Fig. 6. Substrate zonation of wetland development area on borrow pit lake slurry impoundment, Ayrshire Mine.

reclamation through wetland development as a viable reclamation alternative (Nawrot, 1981; Nawrot and Yaich, 1982). This approach to reclamation of a slurry pond through wetland development is based upon the following principles and concepts:

- The pond has a stable water level at or near the surface of the slurry over a major portion of the pond.
- The slurry contains a high clay and silt content.
- The materials with a high acid-producing potential, principally pyrite, are not uniformly distributed throughout the pond.
- The acid-base balance for the slurry pond as a whole can be maintained within acceptable limits.

The typical topography of a single-point slurry discharge pond is illustrated in Fig. 6. As slurry is discharged into the pond, chemical and physical gradients are established, extending from the discharge point to the decant point. The gradients are a result of the differences in size, shape, and specific gravity of the indiviudal particles of which slurry is composed. As a result of these gradients, the discharge point is characterized by coarse, dense particles while the decant point is characterized by fine, light particles. The specific gravity of the slurry constituents can vary by a factor of three or more, with pyrite having the highest specific gravity. Therefore, the discharge area typically has a high concentration of pyrite and, consequently, a high potential acidity. The decant area typically has a concentration of fine, light particles dominated by silts and clays (Nawrot and Yaich, 1982).

The high potential acidity of the materials in the discharge area not only inhibits the establishment of vegetation in the immediate area but, due to the high topographic position of the discharge area, the entire pond is impacted by acid runoff and the migration of pyritic materials downslope. The potential acidity of the discharge area is commonly in excess of the neutralization potential of the pond water. However, by having the acid-producing materials concentrated in one area, treatment is possible by covering them with non-toxic earth fill. The cover material will inhibit the oxidation of the pyritic materials and minimize the infiltration of surface water, which nearly eliminates the potential for acid production.

Once the acid-producing potential associated with the discharge area is reduced, the acid-neutralization potential on the remainder of the area is adequate to allow the establishment of vegetation with the use of soil amendments. The area is divided into zones based on proximity to the stable water level, and is then revegetated with approporate species for each zone, as indicated in Fig. 6.

## CURRENT WILDLIFE MANAGEMENT AT REPRESENTATIVE MINES

### Giant Canada Goose

The Giant Canada Goose (*Branta canadensis maxima*) is the largest of 11 races of Canada Goose. Prior to the appearance of European man, it was a common resident throughout the Midwest. It does not migrate north to nest as do other races, but nests in the Midwest. As a result of excessive hunting and habitat loss, the Giant Canada Goose was thought to be extinct up until the 1960s, when a remnant population was identified (Hanson, 1965).

Since 1979, AMAX Coal Company has been working with the Indiana Department of Natural Resources in their efforts to re-establish the Giant Canada Goose in its native range throughout Indiana. The objective of the re-establishment program is to establish self-perpetuating populations at as many sites as possible. From these nuclei, it is hoped the birds will expand into the surrounding countryside. A similar release was made on mined land in Illinois in 1967-71 and, today, that mine area supports a flock of 3,000 Giant Canada Geese (Klimstra and Thornburg, 1982). The large surface coal mines offer an excellent opportunity for establishment of goose populations due to the large surface acreage they control, which allows a level of protection the average small landowner cannot provide. In addition, the large expanse of grasses and legumes common to surface mines, interspersed with an abundance of water, provides excellent habitat for the Giant Canada Goose.

AMAX Coal Company received and released the first geese at Ayrshire Mine in 1979. They were held in a pen for approximately one month to acclimate them to the area. The geese were wing-clipped and released just prior to the nesting season. Additional releases were made without wing-clipping the birds. Floating nest platforms have been provided for the geese in the absence of islands, their preferred nest sites. The geese have readily taken to the floating nests, and most successful nests are believed to have been on the platforms. However, there has been some successful ground nesting.

Since 1979, 50 adult geese and 30 young of the year have been released at Ayrshire Mine. In 1982, Ayrshire Mine supported a population of approximately 85 geese with 26 being young of the year. The population is not at the present considered to be self-perpetuating. However, the high percentage of young of the year is a positive indication of success.

### Sport Fishery

Although the impoundments produced today are considered to be an improvement over the past, many of the old impoundments are productive sport fisheries. The old impoundments, most of which were final cuts and inclines, closely resemble a shoebox with steep banks providing little or no littoral zone. For fish such as largemouth bass (*Micropterus salmoides*) and bluegill (*Lepomis macrochirus*) spawning sites are few and the sparse aquatic vegetation provides only limited protection for fingerlings and fry. With such limited recruitment, the fish which do persist attain good size, although few in number. The potential of these old impoundments is evidenced by the number of state record fish taken from "strip pits" in Indiana and Illinois. In Indiana, the bluegill is the only species for which the state record fish has been taken from a "strip pit". However, in Illinois the state record fish for five species has been taken from "strip pits," including: redear (*Lepomis microlophus*), bluegill, yellow bass (*Roccus mississippiensis*), spotted bass (*Micropterus punctulatus*), and rock bass (*Ambloplitesrupestris*).

New impoundments are graded to eliminate steep slopes and, therefore, a more extensive littoral zone is provided. Due to the relatively low fertility of new impoundments, a two phase stocking program is used in an attempt to alleviate a food shortage initially. In the spring, channel catfish (*Ictalurus punctatus*) and fathead minnows (*Pimephales promelas*) are stocked. The fathead minnows are highly prolific and, by the end of the summer, they have spawned several times, providing an initial food base for the largemouth bass. The largemouth bass are stocked in the late summer with the bluegill and redear sunfish. The fathead minnows, being very susceptible to predation, are eliminated within two years. After the first year, the bluegill provide adequate forage for the largemouth bass. This stocking method has been employed in ponds at all the AMAX mines in Illinois and Indiana.

The third stocking phase, using threadfin shad (*Dorosoma petenense*), is being investigated. Excellent results have been reported with the use of threadfin shad in similar impoundments in unmined areas. Serving as a forage fish for the largemouth bass and channel catfish, threadfin shad provide particular advantages:

- They are low on the food chain, being plankton feeders.
- Being highly prolific, only a very small number are required for annual stocking.
- They cannot survive winter temperatures, therefore, they cannot become overpopulated.
- They do not attain a size which prohibits them from being utilized as forage.

This stocking method is being used in some ponds at the Ayrshire and Minnehaha Mines in Indiana, and the Delta Mine in Illinois.

All new impoundments are being stocked with the objective of maximizing their potential as a sport fishery. By doing this, and through the waterfowl management program, AMAX Coal is hoping to provide quality water - based recreation areas that can be enjoyed by the citizens of Illinois and Indiana.

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## SESSION IV: WATER RESOURCE MANAGEMENT & POLICY

Chairman
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# A COMPREHENSIVE, CONCEPTUAL MODEL OF WETLAND VALUATION

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## ABSTRACT

Much work is left to be done to estimate monetary wetland values that are verifiable, comparable, and acceptable to all parties involved in wetland allocation disputes. Interdisciplinary cooperation needs to be improved so that dichotomous interests can be combined to work toward a common end. A model is suggested that presents a framework for practitioners from all involved disciplines to design and carry out complementing pieces of research. Both independent research efforts and larger interdisciplinary projects can be accommodated by the model. The wetland valuation model simulates the dynamic and highly interactive nature of the system--from ecosystem to social system. An interdisciplinary approach allows detailed analysis of components of the ecosystem that in turn leads to analyses of product outputs and subsequent estimation of socioeconomic values on a broad scale. The successful monetary valuation of prairie wetlands will hinge on (1) successful simulation of the wetland ecosystem, (2) identification of those members of society who derive benefits from wetland products and services, and (3) the ability to estimate those benefits. Each is a formidable task.

## INTRODUCTION

Wetlands compete for land with a variety of other uses. In the Northern Plains, agricultural production is the primary competitor; however, urban uses, highways, and energy development also compete for land currently in the form of wetlands. Wetlands appear to be losing the battle to other uses, although the interest in wetland preservation is increasing (Nelson et al., 1981).

North and South Dakota were estimated to contain 2 million and 0.8 million hectares of wetland, respectively, prior to the settlement by Europeans. Current estimates indicate that nearly 50 percent of the wetlands in these states have been drained and drainage is continuing. Less than half of the remaining wetland base is protected by federal, state, or private programs.

There is no clear agreement on the future of these remaining wetlands. The value of converting wetlands to agricultural cropland is usually higher for the landowner than to maintain the wetland. In order to justify public ownership or leasing, the value of wetlands to each of the groups which benefit from wetlands needs to be estimated.

## STATUS OF RESEARCH ON WETLANDS

Considerable time, effort, and funding have been devoted to wetland research. A recent review of literature by Leitch et al. (1981a, 1981b, 1981c) and Ogaard et al. (1981a, 1981b, 1981c) identified a large number of studies on the biological, chemical, economic, etc. aspects of wetlands and wetland products. However, the lack of communication among academic disciplines and between academicians, resource managers, and administrators has impeded progress toward comprehensive understanding of the wetlands and their role in the economic system. The lack of communication has resulted in critical gaps in knowledge and has led to inefficient private decisions and government action regarding the use of wetlands.

Attempts to value wetlands and their products have been limited by the lack of information on the wetland ecosystem itself (Gooselink, Odum, and Pope, 1974; Gupta, 1971; Jaworski and Raphael, 1978). Larson (1976, p. 3) states that "placing a value on these systems (wetlands) requires an interdisciplinary approach in developing evaluation models."

## THE MODEL

Complex environmental systems require models which are manageable, realistic, and general (Boynton et al., 1979; Intriligator, 1978). The conceptual model, presented in Fig. 1, is an attempt to achieve those objectives. It is a holistic model with the goal of accurately providing information to policymakers and resource owners. The model contains four major components: (1) the biological system, (2) a product-user interface, (3) the socioeconomic system, and (4) a feedback mechanism.

The biological system consists of the biological, physical and chemical relationships which operate in the wetland setting. One can view it as sets of interrelated production relationships which are solved simultaneously. The initial resource levels are a function of the wetland setting i.e., the chemical, climatic, topographic conditions of the wetland. This system produces a large number and variety of products, ranging from flood control

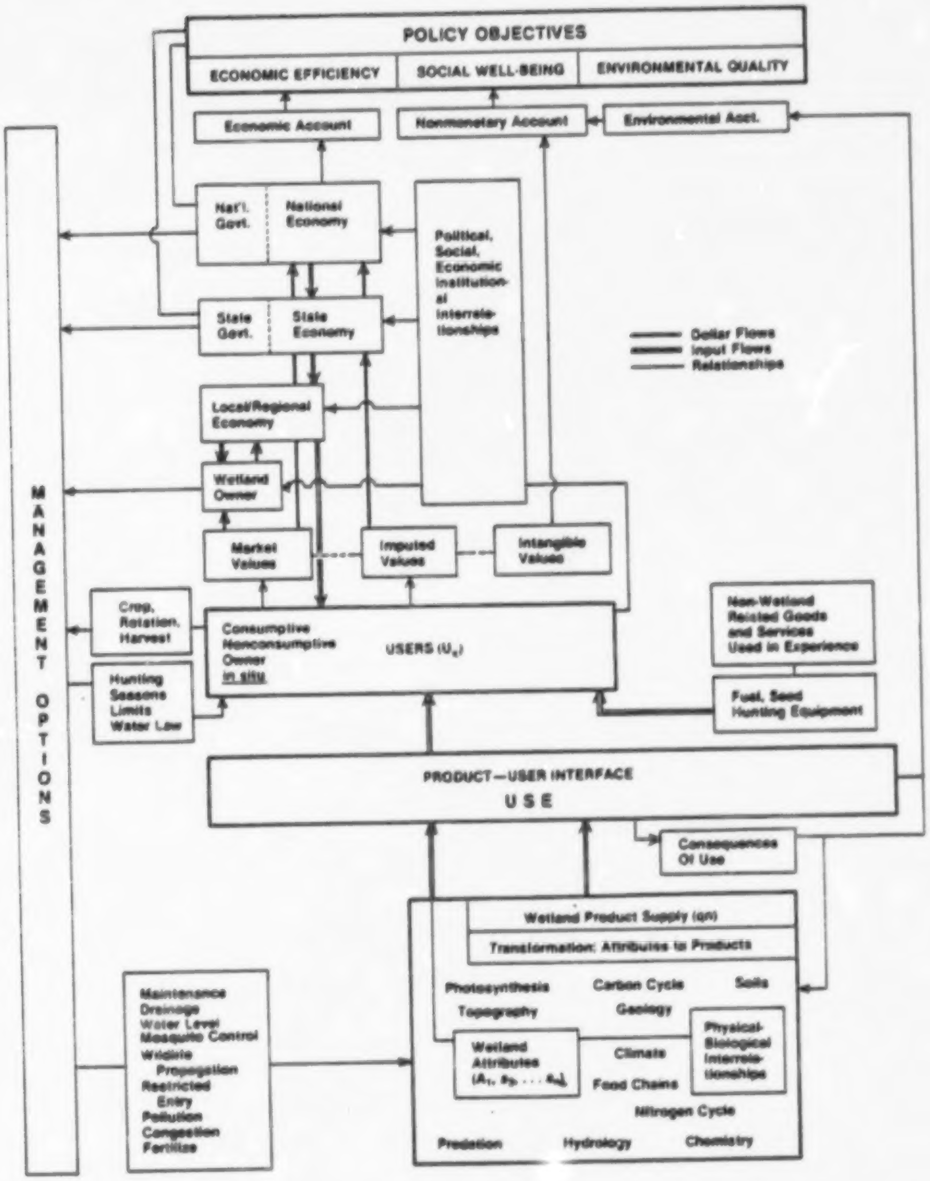

Fig. 1. A comprehensive, conceptual model of wetland valuation.

and groundwater recharge to mallards (Anas platyrhynchos), and also intermediate products which are essential to upland mammals and birds. Special emphasis needs to be given to the compatibility-incompatibility of various uses of wetlands. Many of the wetland products and services are compatible i.e., they are produced simultaneously as joint products. Waterfowl, water storage, and cover for upland animals are all produced simultaneously; however, conversion to cropland or residential subdivisions are obviously incompatible products and services be identified and production be measured.

The second component, perhaps the most critical, of the model is the product-user interface. This component ties the human decision-maker to the natural ecosystem. Qualitative and quantitative characteristics of the wetland and its products need to be provided to the user in such a manner that one is aware of the range of alternative actions available. Users may vary from farmers, hunters, scientists, to United States Senators.

The third component of the model consists of the total set of wetland users, both direct and indirect. Large numbers of people may have no direct connection to the wetland ecosystem; however, they may be affected economically or socially in a variety of ways. They may receive benefits through the impact of wetland-related activities such as hunting expenditures or a portion of their taxes may be used to preserve wetlands. Wetland users can be divided into several groups, such as resource owners, hunters, environmentalists, and businessmen. One person, however, can be a member of several affected groups simultaneously. A person can be a landowner, a hunter, and a public official. This makes the process of valuing wetlands complex; however, the key is to define user groups along wetland product types.

The final component of the model is a feedback mechanism. This mechanism is required to estimate the effects of user decisions upon the biological system and, in turn, through the interface to future impacts upon the user. The feedback mechanism is an important component of the model. Use of wetland ecosystems and their products can broadly be separated into competitive and noncompetitive uses. Conversion of wetlands to agricultural cropland is a competitive, in fact exclusive, use of the resources. It eliminates all other potential values. On the other end of the continuum are uses such as bird watching, and option and existence values. Activities such as hunting, and an occasional use by domestic animals for forage, lie between these points. The feedback mechanism is necessary to estimate the effect of various uses upon the resource and upon the range of future uses.

The conceptual model is human oriented; that is, humans, individually or in groups, are both the beneficiaries of the products produced by the wetland and the major manageable factors influencing changes in the system. Its purpose is to provide information to decision makers, resource owners, users, and government officials on the alternatives available to them and the consequences of each of the alternatives.

## An Example

The use of one wetland product, the mallard duck, may help to illustrate the model. The prairie pothold region of the Northern Plains provides a critical portion of the production base for the mallard. This region is comprised of a variety of wetland types plus the surrounding upland habitat which support the mallard at various times during its life cycle. Information on the wetland attributes and the physical-biological relationships, including natural predators, hydrology, and food chains, are needed to estimate the actual and potential production of mallards from a given region.

The use of mallards by humans may be direct as in hunting or bird watching, or indirect as when the mallard is part of the food supply for other birds of prey and carnivorous mammals. The use of mallards, for example, in hunting activities generates various types of benefits. Cash flows are generated by hunters through expenditures for lease payments to property owners and food, clothing, lodging, petroleum, and hunting supplies in the local and their home area. These cash flows are multiplied as they move through the local, regional, and national economy. In addition, there are nonmonetary benefits received which are separate and frequently greater than the actual cash flows. These benefits, identified in Fig. 1 as imputed values and intangible values, also need to be measured and aggregated at the local, regional, and national levels. Benefits of these two types vary from imputed value of the user's time to option and existence values.

Each of the potential uses of the mallard will generate impacts back through biological systems in a variety of ways. These consequences also need to be estimated for the full effect of a specific use of one wetland product to be measured.

## SUMMARY

The purpose of this model is twofold. First, when quantified, it will provide information to resource owners, public officials, and resource users concerning the value of various uses of wetlands and the consequences of specific uses. Second, it provides a framework for research on wetland ecosystems. Each of us involved in research on aquatic systems needs to be aware of how our research fits into a comprehensive view of wetlands and to design our projects so that the results are useful to other researchers as well as decision makers.

Decisions are being made daily with and without information on the alternatives and consequences which affect wetland ecosystems. We, as scientists, need to design and carry out our research projects with the goal of providing useful information to these decision makers and to other researchers. We, in the social sciences, are very much dependent upon the biological and physical sciences to provide the information so that we can provide values and trade-offs to decision makers.

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# LAND DRAINAGE IN SASKATCHEWAN

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## ABSTRACT

In 1981, after years of studying drainage on the plains, the Province of Saskatchewan passed the Drainage Control Act to regulate drainage. The Saskatchewan Drainage Control Act, which is administered by the Department of the Environment, accomplishes four main objectives; it enables the delegation of duties and responsibilities under the Drainage Control Act to local watershed commissions, it enables the drainage of surface water to be controlled through a permit system, it provides a mechanism to resolve drainage and related flooding problems through a complaint system, and it provides a mechanism for appeals to an Appeal Board against decisions, orders or actions under the Drainage Control Act. In this way, the Act establishes procedures for requesting drainage permits, registering drainage complaints, establishing watershed commissions and appealing watershed commission drainage decisions. The Drainage Control Act will assist in maximizing the utilization of the water resources in the province.

## INTRODUCTION

In 1931 the Federal Government gave the Province of Saskatchewan the responsibility of managing surface water resources within the province. At that time, the Saskatchewan Water Rights Act was passed to allocate the use of surface water through a licensing process. Other provincial statutes with regulatory powers pertaining to water resources include the Ground Water Conservation Act, the Water Resources Management Act and the Water Power Act. However, the Province of Saskatchewan did not pass legislation specifically regulating drainage until 1981. Before this legislation was enacted, an extensive study of flooding and drainage was completed, and legislation from other provinces and states in the Great Plains was studied. As a result, the Province of Saskatchewan now has a well defined drainage act entitled the Drainage Control Act.

The Drainage Control Act, which is administred by the Department of the Environment, accomplishes four main objectives: it enables a delegation of duties and responsibilities to local watershed commissions under the Drainage Control Act, it enables the drainage of surface water to be controlled through a permit system, it provides a mechanism to resolve drainage and related flooding problems through a complaint system, and it provides a mechanism for appeals against watershed commission decisions, orders or actions, under the Drainage Control Act to an Appeal Board, consisting of five members. In this way, the Act establishes procedures for requesting drainage permits, registering drainage complaints, establishing watershed commissions, and appealing watershed drainage decisions.

## DISCUSSION

The Drainage Control Act makes it an offence for any person to construct or use drainage works unless a permit has been obtained to do so. The Drainage Control Act defines drainage works as "any works or other action constructed, done, operated or intended for the removal or lessening of surface water from land and, without restricting the generality of the foregoing, includes the deepening, straightening, widening and diversion of the course of a stream, creek or other watercourse and the construction of dykes". Works is defined to include "a drain, canal, bridge, culvert, flume adequate pipe, pump or other contrivance constructed, operated or intended for the purpose of draining water".

The Drainage Control Act does not apply to all drainage works; those drainage works not requiring permits are:

1. Drainage works that were in existence on January 1, 1981.

2. Drainage works constructed pursuant to instructions or orders of the Minister of Environment.

3. Drainage works constructed pursuant to The Civil Defence Act in case of disaster or emergency.

4. Drainage works under, through or appurtenant to roads, streets, public highways, lanes, approach roads, railroads and other utilities, where the purpose of the drainage is to maintain or accommodate flows of surface water and where the drainage works do not significantly inhibit the passage of the flows and do not divert water from the outlet through which the water would normally drain.

5. Work undertaken to control soil erosion and clear or remove silt, blow dirt, beaver dams, debris, trees, shrubs and other obstructions from channels and watercourses, where water is not diverted from the normal outlet and where a significant increase in the volume of water downstream does not occur.

6. Drainage works by an owner of land where the water drained and the drainage works are both located entirely on the owner's land and the water drained does not drain from the owner's land.

7. Drainage works located entirely within the boundaries of an urban municipality, where the drainage works do not divert water from the normal outlet.

8. Land levelling and landscape for the development of building sites, public parks and public recreation areas.

9. Drainage works that are required to be approved under The Ground Water Conservation Act, Water Power Act, Department of the Environment Act, and Water Resources Management Act, or regulations under those Acts.

10. Water works and sewage works that are required to be approved under The Water Resources Management Act, or regulations made under that Act.

11. Drainage works constructed under the Canada Railway Act, The Rural Municipalities Act, Urban Municipality Act, or any other Act that enables the Crown or any agency of the Crown to construct drainage works, where construction of the works will be completed prior to December 31, 1981, or any later date that the minister may specify.

12. Drainage works constructed under The Conservation and Development Act, where, prior to January 1, 1981, a commitment to construct the works was made by the Minister of Agriculture to a Conservation and Development Area Authority.

13. Drainage works constructed under the South Saskatchewan Irrigation Act or The Water Users Act, where the works are located within the boundaries of the districts and are constructed for the purpose of draining excess irrigation waters, including irrigation return flows, and where the works do not divert water from the normal outlet.

The Drainage Control Act enables local watershed commissions to be appointed to control and co-ordinate drainage practices within the watershed by granting and suspending permits. It is proposed that watershed commissions be comprised of up to 13 people living in the watershed area. Municipal governments, conservation and development areas and wildlife and other groups will be represented. Anyone who suffers damage, loss or injury from drainage works may file a complaint with the Watershed Commission. A person found guilty of contravening the Act is subject to a fine of up to $5000. There is no provision in the Drainage Control Act to award compensation for damages resulting from flooding. Legal action can be taken through the courts for this purpose. After a complaint is made to a watershed commission, an investigation and survey may be conducted, and steps will be taken to find an acceptable solution. If an acceptable solution to the complaint is not found a hearing may be requested. At the hearing all parties to the complaint are placed under oath for the purpose of presenting evidence, cross-examining witnesses, and being cross-examined.

Any person may appeal any decision, action or order made by a watershed commission under the Act with respect to the issuance or denial of a permit or a complaint investigation. An appeal must be made within 30 days of the decision, action or order and must be accompanied by a fee of $100 which is returned if the appellant is successful. Appeals are heard by a Drainage Appeal Board of five members, one of whom is the author. The Appeal Board may make its own rules of conduct, subject to the Lieutenant Governor in Council. The procedures followed for Appeal Board hearings are similar to those procedures followed in watershed commission hearings. The Board may engage the staff and advisors as it considers necessary. In rendering a decision, the Appeal Board may affirm the decision of the Watershed Commission, vary the decision, substitute its own decision or make any order it considers appropriate. Any person aggrieved by a decision of the Appeal Board may appeal to a judge of Queen's Bench for Saskatchewan on a question of law by filing a Notice of Appeal within 30 days after the day on which the decision was made. If an appeal is not filed within the 30-day period the decision of the Appeal Board becomes enforceable as a judgment of the court.

## CONCLUSIONS

The drainage of land in Saskatchewan is a complex problem involving five major provincial statutes. One of these statues, the Drainage Control Act, provides a mechanism to ensure that drainage activities within each watershed are controlled and co-ordinated, to ensure that the impacts of proposed drainage works are evaluated, and to provide a means to deal with complaints and disputes caused by drainage works. As a result, the Drainage Control Act will assist in maximizing the utilization of land and water resources in the Province of Saskatchewan.

# CHEMISTRY OF ACID RAIN IN NORTH DAKOTA

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## ABSTRACT

Rainwater chemistry has been monitored at two rural sites in North Dakota since April 1981. Samples from individual storms are analyzed for 11 major and 15 minor constituents, with attention given to filterable (<0.45-μm) and nonfilterable (>0.45-μm) fractions of the metal parameters. Preliminary results indicate that (1) rain at both sites is characterized by greater hydronium ion activity and by lesser concentrations of alkaline earth metals than generally have been reported for northern plains locations, (2) pH of rainfall increases from western to eastern North Dakota due to a concomitant increase in concentrations of ammonium, (3) observed concentrations of aluminum, cadmium, copper, iron, lead, manganese, nickel, silver, and zinc are consistent with those reported for other locations in the northern plains, and (4) anthropogenic influences on rain chemistry in North Dakota now relate more to land use and agricultural practices than to regional industrialization.

## INTRODUCTION

Documentation of anthropogenic acids in precipitation since the late 1940s (Barrett and Brodin, 1955) and, more recently, their implication in the demise of aquatic communities in areas of Europe and eastern North America (e.g., Wright and Gjessing, 1976; Schofield, 1976) have heightened scientific interest in the chemical properties of rain and snow. In North America alone, over 50 ongoing studies of precipitation chemistry have been implemented, most pertaining to eastern regions of the continent or to specific urban centers of the eastern United States (Wisniewski and Kinsman, 1982).

In the northern plains, the chemistry of rain and snow has received less attention. Our understanding of regional precipitation quality has relied primarily on historical, short-term investigations of continental rain composition (Junge and Gustafson, 1956; Junge and Werby, 1958; Lodge et al., 1968), on modern reinterpretations of the historical data (Liljestrand and Morgan, 1979; Stensland and Semonin, 1982), and on interpolations of data from scattered sites in the prairie provinces of Canada and the

Central Lowlands of the United States (Cowling, 1982; Munger and Eisenreich, 1983). The scarcity of regional data has precluded an accurate assessment of precipation quality or, more importantly, an evaluation of its influence on the natural and agricultural resources of the northern plains.

For the past two years, an effort has been made to increase representation of the northern plains in national precipitation chemistry programs (NADP, 1982). Moreover, a few of the region's state and provincial governments have implemented ongoing studies of precipitation quality (e.g. Kallemeyn, 1982; Lau, 1983; Ray, 1983). This report addresses the preliminary findings of one such study, coordinated by the North Dakota State Department of Health and supported, in part, by a grant from the Bureau of Land Management, United States Department of the Interior.

## METHODS

Selected chemical properties of rainfall are monitored at two rural locations in North Dakota, the first in central Dunn County (latitute 47°19'N, longitude 102°31'W) and the second in northwestern Stutsman County (latitude 47°7'N, longitude 99°14'W). Both locations are representive of major geological and land use regions within the state (Angelo and Anderson, 1982) and meet recognized siting criteria for precipitation monitoring facilities (NCRP, 1978). Each site is equipped with an Aerochem Metrics Model 301 automated precipitation collector, elevated 3 m above ground to minimize terrestrial contamination of rainfall samples; additionally, wind and temperature monitors, a recording rain gauge, and an particulates sampler are operated at each location (Angelo and Anderson, 1982).

Rain samples are collected on an event basis from April through October, a period which typically accounts for 85-90 percent of the annual precipitation at both monitoring sites (NCC,1982). Samples are transferred to the project laboratory in Bismarck, where specific conductance and pH are measured via resistance and glass/reference electrode analysis, respectively (Peden et al., 1979; Pickering, 1980). Remaining sample volume is filtered (0.45-μm) and both filter and filtrate are preserved for further chemical analysis (Angelo and Anderson, 1982). Final analytical determinations are performed at the State Public Health Laboratory, as follows: chloride, fluoride, nitrate, orthophosphate, and sulfate by ion chromatography (Fishman and Pyen, 1978); ammonium by automated colorimetric phenate (Peden et al., 1979); filterable and nonfilterable calcium, magnesium, potassium, sodium, and zinc by flame atomic absorption spectroscopy (EPA, 1979; Peden et al., 1979), filterable and nonfilterable aluminum, cadmium, chromium, copper, iron, lead, manganese, molybdenum, nickel, vanadium, and silver by nonflame atomic absorption spectroscopy (EPA, 1979; Peden et al., 1979); and filterable arsenic and selenium by hydride generation (Workman and Soltanpour, 1980; Perkin-Elmer, 1981).

Stringent quality assurance measures are applied to all field, laboratory, and data handling aspects of the rainfall study. In addition to routine laboratory quality control practices (NDSDH, 1982), procedural blanks accompany each rainfall sample submitted to the State Public Health Laboratory duplicate analyses and/or sample spikes are performed on a minimum of 20 percent of all analytical determinations, and all graphite furnace analyses are performed via standard additions. The Department participates in precipitation sample reference programs, in interlaboratory analytical comparisions of rainfall samples, and in federally sponsored audits of field and laboratory techniques (Angelo and Anderson, 1982; Angelo, 1983).

## RESULTS

One hundred twenty-three rainfall samples were collected from April 1981 through October 1982. Median and volume-weighted mean concentrations of selected ionic constituents have been presented in Table I. To facilitate this summary, concentrations reported

TABLE I. Concentrations of Major Ions in Rain[a]

| | —— Dunn County —— | | —— Stutsman County —— | |
|---|---|---|---|---|
| Ion | Median | Wt. Avg. | Median | Wt. Avg. |
| $NH_4^+$ | 26.6 | 19.4 | 30.5 | 28.8 |
| $H_3O^+$ | 14.3 | 13.1 | 8.4 | 9.9 |
| $Ca^{2+}$ | 4.5 | 4.5 | 5.0 | 4.5 |
| $Na^+$ | 1.7 | 1.7 | 2.2 | 2.2 |
| $Mg^{2+}$ | 1.2 | 1.2 | 1.2 | 1.2 |
| $K^+$ | 0.5 | 1.0 | 1.0 | 1.0 |
| $NO_3^-$ | 17.2 | 13.5 | 19.3 | 15.8 |
| $Cl^-$ | 14.1 | 8.7 | 14.1 | 8.5 |
| $HCO_3^-$ | 12.1 | 9.2 | 15.1 | 14.3 |
| $SO_4^{2-}$ | 8.5 | 7.6 | 10.4 | 8.4 |

[a] Values represent median and volume-weighted mean concentrations in $\mu mol \cdot l^{-1}$

as less than minimum detection limit (MDL) were accorded values of one-half MDL. Due to sample volume constraints, the actual number of analyses per ion ranged from 40-63 per site. Bicarbonate concentrations reflected in this table were calculated from sample pH, measured ion concentrations, and estimated partial pressures of carbon dioxide (Granat, 1972; Stensland and Semonin, 1982; Munger and Eisenreich, 1983).

On a mass concentration basis, the principal measured species in rain samples included the anions nitrate and sulfate and the cations ammonium and calcium. Concentrations of these and other ions differed substantially from levels previously ascribed to the northern plains. For example, mean sulfate and nitrate concentrations were 45-60 percent of those purported as representative of the region by Munger and Eisenreich (1983). Volume-weighted averages for hydronium ion activity at the two North Dakota sites were 3-46 times greater than estimates for the state presented in Cowling (1982) and 17-31 times greater than those reported for three locations in southern Saskatchewan and southern Manitoba (CANSAP, 1982). Alkaline earth and alkali metal ions in rain were less abundant than generally noted for the region; for instance, filterable calcium demonstrated average concentrations only 4-27 percent of those reported for precipitation at the three Canadian sites (CANSAP, 1982).

Observed values for rainfall pH have been depicted in Fig. 1. Median pH values of 5.07 and 4.84 were recorded for the Stutsman County and Dunn County locations, respectively. Intersite differences in pH were primarily reflective of the statistically greater concentrations of ammonium, a basic constituent, at the Stutsman County site. These comparatively high concentrations may have related to the more extensive conversion of prairie to cropland and to the correspondingly greater use of anhydrous ammonia fertilizers in eastern North Dakota (BOC, 1978. Munger and Eisenreich (1983), for example, attributed ammonium concentrations of 30-40 $\mu mol.l^{-1}$ over much of central North America primarily to the cultivation and aeolian erosion of high pH soils, to the production, storage, and application of nitrogenous fertilizers, and to the natural denitrification and volatilization of nitrogen compounds in soils.

In a stoichiometric sense, however, the hydronium ion activity of rainfall in North Dakota was more readily interpretable in terms of all major chemical species. Regression of $[H_3O^+]$ on $[NO_3^-] + 2[SO_4^{2-}] + 3[PO_4^{3-}] + [Cl^-] + [HCO_3^-] - [NH_4^+] - 2[Ca^{2+}] - 2[Mg^{2+}] - [Na^+] - [K^+]$, using pooled 1982 data from the two monitoring sites plus a third site (latitude 47°12'N, longitude 100°24'W) temporarily operated during the 1982 sampling season, produced a significant $r^2$ of 0.97 (Fig. 2 Regression of $[H_3O^+]$ on $[NO_3^-] + 2[SO_4^{2-}] - [NH_4^+]$, previously demonstrating $r^2$ values as great as 0.9 for precipitation data from the northeastern United States (Bowersox, 1980) and rural Norway

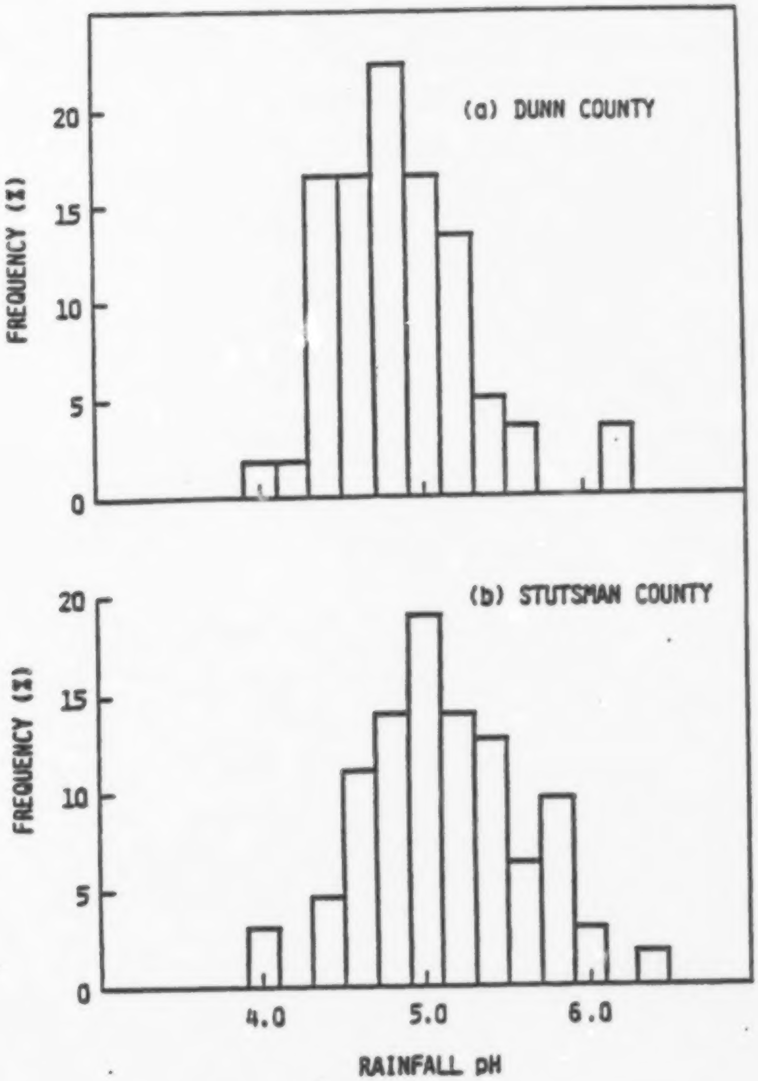

Fig. I. Intersite comparison of rain pH, April 1981-October 1982.

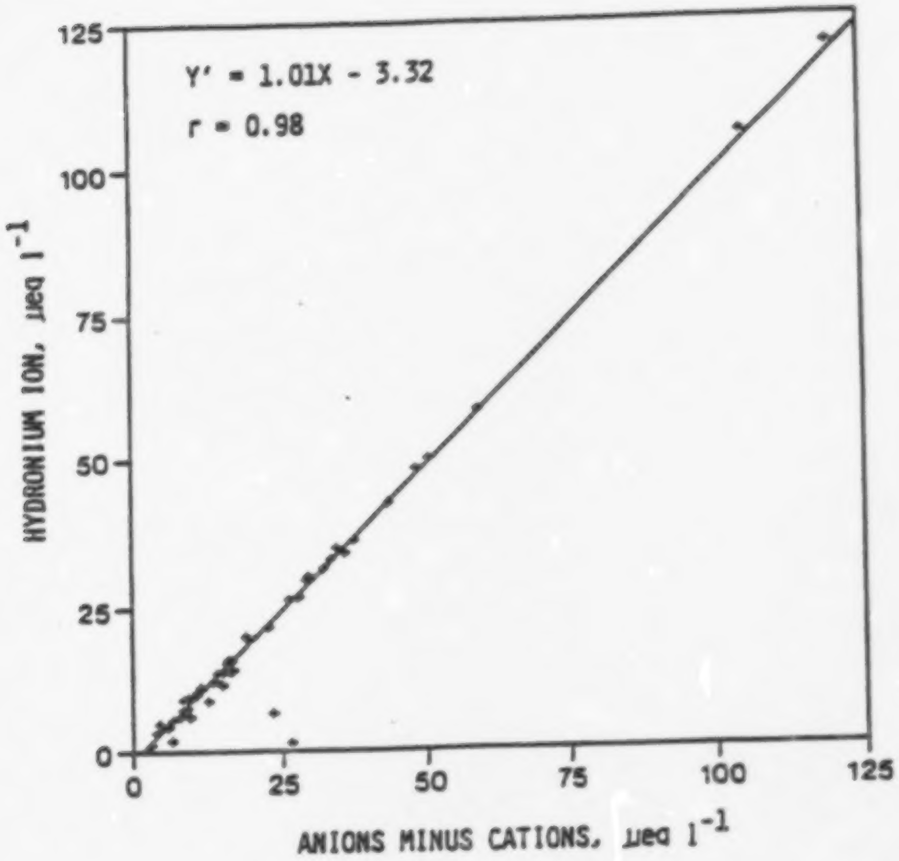

Fig. 2. Measured vs. calculated hydronium ion activity.

(Schaug and Semb,1976), produced in the present study an $r^2$ of only 0.17 and a regressed line with slope of 0.53 and intercept of 12.4 µmol.$l^{-1}$. These analyses suggested that the pH of rain at the Dunn county and Stutsman County sites was not controlled primarily by concentrations of strong acid anions, as has been demonstrated for several areas of the continent (e.g., Galloway et al., 1976; Liljestrand and Morgan, 1978); rather, pH at these two locations was a more equitable reflection of all acids and bases in solution.

Concentrations of trace metals in rainfall at both monitoring locations were represented best by median values (Table 2). Unfortunately, most available literature on trace elements in rain have been reported as volume-weighted mean or arithmetic mean concentrations only, requiring data from the Dunn County and Stutsman

TABLE 2. Concentrations of Selected Metals in Rain[a]

| Location | Al | Cd | Fe | Mn | Pb | Zn |
|---|---|---|---|---|---|---|
| Dunn County | | | | | | |
| Filterable | 0.11 | <8.9E-4 | 0.02 | 0.06 | 4.8E-3 | 0.17 |
| Total | 2.33 | <1.8E-3 | 1.24 | 0.07 | <7.2E-3 | 0.21 |
| Stutsman County | | | | | | |
| Filterable | 0.11 | 1.8E-3 | 0.02 | 0.08 | 4.8E-3 | 0.08 |
| Total | 2.07 | <2.7E-3 | 0.93 | 0.09 | <7.2E-3 | 0.13 |

[a] Values represent median concentrations in $\mu mol \cdot l^{-1}$.

County stations to be compared in those terms. Weighted mean concentrations for total recoverable aluminum, cadmium, copper, lead, manganese, silver, and zinc overlapped those reported by Struempler (1975) for a site in extreme northwestern Nebraska. Furthermore, average concentrations of filterable copper, iron, lead, manganese, nickel and zinc were within ranges reported by Lazrus et al. (1970) for sites near Glasgow, Montana, and Rapid City, South Dakota. Interestingly, greater regional agreement existed regarding the levels of these minor constituents than appeared to be true for the major ionic constituents of precipitation.

Aluminum and iron occurred in rain primarily as insoluble constituents. Occasionally, each of these abundant crustal metals attained nonfilterable levels in excess of 25 $\mu mol.l^{-1}$. Nonfilterable concentrations of aluminum, iron, and manganese demonstrated strong positive correlations with one another ($0.90 \geq r \geq 0.83$; $p < 0.001$); in addition, each of these parameters was significantly and positively correlated with filterable and/or nonfilterable potassium, magnesium, and calcium. These relationships were supportive of a predominately crustal origin for each of the six metals.

Correlations involving filterable concentrations of five metals and ammonium, hydronium ion, nitrate, and sulfate have been presented in Table 3. Ammonium and nitrate exhibited significant positive correlations with each of the metal parameters, suggesting that soil input was a principal source for both ions. Ammonium and calcium each demonstrated significant positive correlations with nitrate and sulfate, intimating the importance of these

TABLE 3. Selected Correlation Coefficients[a]

| Ion | $NO_3^-$ | $SO_4^{2-}$ | $H_3O^+$ | $NH_4^+$ | $Ca^{2+}$ | $Mg^{2+}$ | $Al^{3+}$ | $Fe^{3+}$ |
|---|---|---|---|---|---|---|---|---|
| $Mn^{2+}$ | 0.71 | n.s. | n.s. | 0.76 | 0.80 | 0.85 | n.s. | n.s. |
| $Fe^{3+}$ | 0.44 | 0.35 | n.s. | 0.31 | n.s. | n.s. | 0.57 | |
| $Al^{3+}$ | 0.46 | n.s. | n.s. | 0.31 | 0.26 | n.s. | | |
| $Mg^{2+}$ | 0.61 | n.s. | n.s. | 0.60 | 0.82 | | | |
| $Ca^{2+}$ | 0.70 | 0.42 | n.s. | 0.68 | | | | |
| $NH_4^+$ | 0.87 | 0.63 | n.s. | | | | | |
| $H_3O^+$ | 0.22 | n.s. | | | | | | |
| $SO_4^{2-}$ | 0.62 | | | | | | | |

[a] Values represent pooled Spearman correlation coefficients; "n.s." denotes $p \geq 0.05$.

cations in the neutralization of strong acid anion in rain. A particularly strong correlation between nitrate and ammonium ($r=0.87$; $p<0.001$) was indicative of a predominately common origin and atmospheric behavior for these parameters. This degree of relationship suggested that the two ions may have been chemically associated within the original rain matrix; for example, ammonium nitrate may have entered solution as entrained soil material or, alternatively, may have formed during washout and droplet growth in the presence of atmospheric ammonia and nitric acid.

## CONCLUSIONS

Data derived from this study have provided in initial insight into the chemical properties of precipitation in North Dakota. An observed general consistency in the composition of rainfall over a distance of 250 km suggests that the data are applicable to other rural locations within the state and, perhaps, to much of the northern plains.

Anthropogenic influences on precipitation quality in North Dakota are more subtle than in many areas of the continent and may relate, currently, more to land use and agricultural practices than to regional industrialization. Several properties generally attributed to precipitation in the northern plains, such as high ionic burdens and circumneutral pH, may be fundamentally in error. The existing sparse body of information on regional rain composition does not accurately reflect conditions in North Dakota; consequently, it provides little basis for evaluating the exposure of aquatic and terrestrial resources in the state to atmospheric contaminants.

Because precipitation chemistry is a function of air quality and climate, both of which fluctuate with time, several more years of uninterrupted monitoring are recommended to accurately estimate the chemical variability of rainfall in North Dakota. The information derived from such an effort will produce a refined assessment of rainfall quality and provide a well-documented baseline for future investigations.

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# INITIAL QUALITY CONTROL RESULTS FROM A CANADIAN WATER QUALITY ASSESSMENT NETWORK

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## ABSTRACT

The Western and Northern Region Water Quality Branch of Environment Canada contributes to the National Water Quality Assessment Program by routinely sampling a number of streams and lakes located throughout the prairie provinces and the Northwest Territories. In order to control the overall quality of the results contributed to the Program, the Branch instituted a Field Quality Control Project which consists of collecting a selected number of samples in triplicate. The Project was started in 1977. This report presents the results for nutrient parameters (Carbon, Nitrogen and Phosphorus). The total precision is estimated as the median of the coefficients of variation computed on sets of three observations. For eight of the 12 parameters for which analytical precisions are available, the total precision was less than or equal to the analytical precision. However, when maximum coefficients are combined with total precision in a simple classification scheme, only four parameters can be said to have "good" precision. Possible factors which might influence precision such as concentration, river discharge, and the time interval between sampling and receipt in the laboratory, showed no definite correlation. Examination of the 20 sets with the highest coefficients points to a wide variety of random factors which cause poor precision.

## INTRODUCTION

Substantial effort has generally gone into assessing the accuracy and precision of lab procedures whereas little or no work has been done on establishing the accuracy and precision of field procedures. It is recognized that knowledge of the accuracies and precisions associated with the field and lab procedures is paramount for a scientifically sound interpretation of the data obtained from all programs (Water Quality Branch, 1978). It is incumbent on data collectors to be as accurate and precise as practically feasible since it is not always known, at the time of collection, to what end the data will serve. Separating and quantifying field and lab precision cannot be achieved without considerable difficulty and cost. Therefore, the Water Quality Branch, Western and Northern Region, embarked on a program to establish total precision. The Field Quality Control Project of the Branch was started in June of 1977 with the objective of estimating the total precision of the data collected by the Branch for the full parametric spectrum. This report considers only the nutrient parameters.

There are two purposes to this report. First, estimates will be made of the total precision of the nutrient parameters; and, second, possible causes for poor precision in these parameters will be explored. Although the detection of causes was not an objective of the project, the results should point out any weak links that might exist in the sample handling and analysis process.

In order to clarify the discussion, a number of terms must be defined. These definitions must be considered semantically rigid for the purpose of this report. A "set" refers to two or three samples collected from the same location over a short period of time, usually less than one hour, and treated identically from collection to data reporting. A "group" refers to a number of sets which share some common attribute, such as having all been collected in the same fiscal year or from the same site. "Precision" is the degree of reproducibility of the measurement. It can be expressed mathematically as the coefficient of variation (CV), in %, of a set. The coefficient of variation, which is an indicator of relative dispersion, is used in this report in order to compare results from different rivers sampled at various times over a five-year period. It also allows us to compare the relative performance of different parameters. Correlation between precisions and other sampling factors refers solely to the degree of linear association between a statistic and an independent variable.

## DATA

The data for this report were collected between June of 1977 and March of 1982. The sets were collected from 127 sites in the Western and Northern Region, which encompasses the prairie provinces and the Northwest Territories.

The basis of the project design was to collect in triplicate a number of routine samples collected as part of the on-going Water Quality Assessment Program. The first year of the Field Quality Control Project was designed to be an intensive first determination of measurement uncertainties. In that year, nearly every sample collected by Branch staff was triplicated. Beginning in April of 1978, all sites of the Water Quality Assessment Program were included in the project on a rotating basis. It was also decided to hold the increase in lab workload to 10 percent.

Over the life of the project some 20 to 30 individuals were involved in sample collection. Sample collectors operate out of 10 Water Survey and three Water Quality sub-offices scattered throughout the region. Sample collection and preservation should have followed the standard methods described in the field manuals always (Water Quality Branch, 1979a, Water Quality Branch, 1979b). However, within the standard methods there is considerable leeway. For instance, samples can be collected using a 2-L bottle on the standard sampling iron and then poured into the appropriate bottles for shipment or the bottles can be directly hand dipped (in shallow streams) or some combination of the two techniques. A second example is the preservation of samples using either ampoules or a reagent dispenser bottle. Among the other possible causes of poor precision that this report deals with, two variables in sample handling are included: filtration in the field versus in the lab and transit time to the laboratory.

All of the chemical analyses involved in this study were conducted at the Water Quality Branch Regional Laboratory in Calgary. Table 1 lists the parameters studied, along with their abbreviations and National Water Quality Data Bank (NAQUADAT) parameter code. Descriptions of the analytical methods used can be found by referring to the appropriate parameter code in the NAQUADAT dictionary reference, or to the Analytical Methods Manual (Water Quality Branch, 1979c). Most of the parameters under discussion were analysed by the same method over the period of interest. However, DIC, DOCL and TOC were done by two different methods over the course of the study. Also, there may have been minor changes made in analytical methods which were not considered significant enough to change the parameter code. Changes in the analytical method add to the variance of measurement over the period of study. The Calgary laboratory was able to provide analytical precision data for 12 of the 18 nutrient parameters studied. These data are listed in Table 2.

The computation of the coefficient of variation in percent is as follows:

$$CV = s \,/\, \overline{y} \times 100\%$$

where $\underline{s}$ = standard deviation of replicate samples ($n = 2$ or $3$)
and $\overline{y}$ = arithmetic average of replicate samples.

When a concentration was reported as less than the detection limit, half of the limit was used in the computation of $s$ and $\overline{y}$ since the author considered this to be the least biased estimate of the true concentration.

## RESULTS

The interpretation of the results of this project rests on two major assumptions. The first is that a coefficient of variation computed on two observations is equivalent to one computed

TABLE 1. List of parameters studied

| Parameter Name | Abbr. | Parameter Code |
|---|---|---|
| Total Organic Carbon | TOC | 06001L,<br>06005L |
| Dissolved Organic Carbon - Field Filtered | DOCD | 06104D |
| Dissolved Organic Carbon - Lab Filtered | DOCL | 06101L,<br>06104L |
| Dissolved Inorganic Carbon - Lab Filtered | DICL | 06151L,<br>06152L |
| Particulate Organic Carbon - Field Filtered | POCF | 06902F |
| Particulate Organic Carbon - Lab Filtered | POCL | 06902L |
| Nitrate Nitrite - Field Filtered | NOD | 07110D |
| Nitrate Nitrite - Lab Filtered | NOL | 07110L |
| Ammonia | NH3 | 07506L |
| Dissolved Nitrogen - Field Filtered | DND | 07651D |
| Dissolved Nitrogen - Lab Filtered | DNL | 07651L |
| Paticulate Nitrogen - Field Filtered | PNF | 07902F |
| Paticulate Nitrogen - Lab Filtered | PNL | 07902L |
| Dissolved Phosphorus - Field Filtered | DPD | 15103D |
| Dissolved Phosphorus - Lab Filtered | DPL | 15103L |
| Ortho-Phosphorus - Field Filtered | OPD | 15256D |
| Ortho-Phosphorus - Lab Filtered | OPL | 15256L |
| Total Phosphorus | TP | 15406L |

on three. This assumption is made in order to include as much of the data as possible. The second assumption has to do with the manner in which the data are treated after analysis. The Branch uses a rather sophisticated data screening procedure involving, since 1978, a computer, several people in the lab and the officers responsible for the water quality assessment programs. The computer treats quality control samples identically to all other samples. However, the humans in the process will tend to look at them as a set, thereby increasing the probability that anamolous data will be intercepted prior to reporting. This means that any estimate of total precision based on these data will be biased low. It is impossible to say what the magnitude of the bias might be.

Table 3 summarizes the results grouped by fiscal year. The median coefficient of variation in this table is the estimate of total precision. Generally speaking, the total precision of a parameter is fairly constant from year to year whereas the maximum coefficients of variation fluctuate considerably. There are some patterns in the results which may be significant. For instance, there are six parameters whose field filtered version (DOCD, POCF, NOD, DND, PNF and DPD, see Table 1 for expansion of abbreviations) can be compared to the lab filtered version (DOCL, POCL, NOL, DNL, PNL and DPL). The total precisions of the four dissolved

TABLE 2. Analytical precision of nutrient tests

| No. of sets | No. of observations per set | Range of sets or mean of 1 set in mg/L | Precision in % |
|---|---|---|---|
| Dissolved Organic Carbon - Lab Filtered (DOCL) | | | |
| 6 | 2 | 0.3 - 0.9 | 17.94 |
| 9 | 2 | 2.75 - 5.40 | 5.05 |
| 13 | 2 | 8.35 - 13.50 | 4.13 |
| Dissolved Inorganic Carbon - Lab Filtered (DICL) | | | |
| 4 | 2 | 27.0 - 33.5 | 1.74 |
| Nitrate Nitrite - Field Filtered (NOD) | | | |
| 4 | 2 | 0.24 - 0.38 | 2.62 |
| Nitrate Nitrite - Lab Filtered (NOL) | | | |
| 1 | 7 | 0.025 0.00 | |
| 5 | 2 | 0.04 - 0.20 | 4.17 |
| 1 | 7 | 0.200 0.00 | |
| 1 | 7 | 0.501 0.80 | |
| Ammonia (NH3) | | | |
| 5 | 2 | 0.17 - 0.60 | 9.01 |
| Dissolved Nitrogen - Field Filtered (DND) | | | |
| 4 | 2 | 0.07 - 0.15 | 0.00 |
| 4 | 2 | 0.24 - 0.36 | 1.29 |
| 10 | 2 | 0.78 - 1.10 | 4.23 |
| Dissolved Nitrogen - Lab Filtered (DNL) | | | |
| 1 | 10 | 0.050 0.00 | |
| 1 | 10 | 0.296 1.69 | |
| 1 | 10 | 0.755 1.32 | |
| Dissolved Phosphorus - Field Filtered (DPD) | | | |
| 4 | 2 | 0.053 - 0.062 | 0.60 |
| 4 | 2 | 0.40 - 0.42 | 0.00 |
| Dissolved Phosphorus - Lab Filtered (DPL) | | | |
| 4 | 2 | 0.008 - 0.025 | 0.00 |
| 5 | 2 | 0.11 - 0.20 | 0.00 |
| Ortho-Phosphorus - Field Filtered (OPD) | | | |
| 4 | 2 | 0.0145 - 0.034 | 1.92 |
| Ortho-Phosphorus - Lab Filtered (OPL) | | | |
| 4 | 2 | 0.019 - 0.094 | 0.00 |
| Total Phosphorus (TP) | | | |
| 1 | 7 | 0.008 12.5 | |
| 1 | 7 | 0.196 2.55 | |
| 4 | 2 | 0.16 - 0.29 | 0.00 |
| 1 | 7 | 0.400 1.50 | |

TABLE 3. Summary by Year

| Fiscal Year | No. of Sets | Range of Sets or mean of 1 set in mg/L | Coefficient of Variation in percent | | |
|---|---|---|---|---|---|
| | | | Minimum | Median | Maximum |
| Total Organic Carbon (TOC) | | | | | |
| 1977 | 5 | 2.83 - 22. | 0 | 9 | 100 |
| 1978 | 2 | 7.5 - 11.7 | 5 | 43 | 82 |
| 1980 | 10 | 2. - 26.7 | 0 | 3 | 43 |
| 1981 | 1 | 12. | 0 | 0 | 0 |
| 1977 to 1981 | 18 | 2. - 26.7 | 0 | 7 | 100 |
| Dissolved Organic Carbon - Field Filtered (DOCD) | | | | | |
| 1980 | 19 | 2. - 17. | 0 | 0 | 78 |
| Dissolved Organic Carbon - Lab Filtered (DOCL) | | | | | |
| 1978 | 36 | 0.5 - 26.3 | 0 | 1 | 66 |
| 1979 | 43 | 0.5 - 26.3 | 0 | 0 | 43 |
| 1980 | 16 | 2. - 26.7 | 0 | 4 | 50 |
| 1981 | 37 | 0.4 - 25. | 0 | 1 | 15 |
| 1977 to 1981 | 132 | 0.4 - 26.7 | 0 | 0 | 66 |
| Dissolved Inorganic Carbon - Lab Filtered (DICL) | | | | | |
| 1978 | 36 | 6.33 - 70. | 0 | 2 | 21 |
| 1979 | 43 | 0.5 - 84. | 0 | 0 | 31 |
| 1981 | 2 | 30. - 42.7 | 0 | 1 | 1 |
| 1977 to 1981 | 81 | 0.5 - 84. | 0 | 1 | 31 |
| Particulate Organic Carbon - Field Filtered (POCF) | | | | | |
| 1977 | 11 | 0.19 - 6.73 | 9 | 32 | 52 |
| Particulate Organic Carbon - Lab Filtered (POCL) | | | | | |
| 1977 | 86 | 0.075 - 3.8 | 0 | 14 | 90 |
| 1978 | 36 | 0.0533 - 9.89 | 3 | 10 | 70 |
| 1979 | 43 | 0.04 - 7.13 | 2 | 13 | 79 |
| 1980 | 30 | 0.15 - 13.3 | 0 | 5 | 48 |
| 1981 | 39 | 0.0733 - 8.97 | 0 | 7 | 80 |
| 1977 to 1981 | 234 | 0.04 - 13.3 | 0 | 10 | 90 |
| Nitrate Nitrite - Field Filtered (NOD) | | | | | |
| 1980 | 19 | 0.005 - 1.03 | 0 | 0 | 71 |
| 1981 | 30 | 0.005 - 1.47 | 0 | 0 | 43 |
| 1977 to 1981 | 49 | 0.005 - 1.47 | 0 | 0 | 71 |
| Nitrate Nitrite - Lab Filtered (NOL) | | | | | |
| 1977 | 5 | 0.005 - 1.3 | 0 | 0 | 77 |
| 1978 | 38 | 0.005 - 1.67 | 0 | 3 | 95 |
| 1979 | 43 | 0.005 - 0.513 | 0 | 6 | 152 |
| 1980 | 15 | 0.005 - 0.143 | 0 | 0 | 157 |
| 1981 | 9 | 0.005 - 0.07 | 0 | 0 | 144 |
| 1977 to 1981 | 110 | 0.005 - 1.67 | 0 | 3 | 157 |
| Ammonia (NH3) | | | | | |
| 1977 | 1 | 0.05 | 0 | 0 | 0 |
| 1978 | 4 | 0.05 - 0.367 | 0 | 8 | 42 |
| 1979 | 7 | 0.05 - 0.767 | 0 | 0 | 8 |
| 1980 | 2 | 0.0667 - 0.0667 | 43 | 43 | 43 |
| 1981 | 28 | 0.05 - 0.5 | 0 | 0 | 11 |
| 1977 to 1981 | 42 | 0.05 - 0.767 | 0 | 0 | 43 |

Table 3. (continued)

| Fiscal Year | No. of sets | Range of Sets or mean of 1 set in mg/L | Coefficient of Variation in percent | | |
|---|---|---|---|---|---|
| | | | Minimum | Median | Maximum |
| Dissolved Nitrogen - Field Filtered (DND) | | | | | |
| 1980 | 18 | 0.12 - 1.67 | 0 | 2 | 12 |
| 1981 | 28 | 0.07 - 1.6 | 0 | 2 | 16 |
| 1977 to 1981 | 46 | 0.07 - 1.67 | 0 | 2 | 16 |
| Dissolved Nitrogen - Lab Filtered (DNL) | | | | | |
| 1978 | 36 | 0.0667 - 1.6 | 0 | 5 | 65 |
| 1979 | 43 | 0.07 - 1.1 | 0 | 4 | 36 |
| 1980 | 34 | 0.0933 - 1.5 | 0 | 3 | 110 |
| 1981 | 39 | 0.07 - 1.6 | 0 | 4 | 36 |
| 1977 to 1981 | 152 | 0.0667 - 1.6 | 0 | 4 | 110 |
| Particulate Nitrogen - Field Filtered (PNF) | | | | | |
| 1977 | 11 | 0.0383 - 2.22 | 5 | 53 | 132 |
| Particulate Nitrogen - Lab Filtered (PNL) | | | | | |
| 1977 | 83 | 0.005 - 4.93 | 0 | 17 | 166 |
| 1978 | 36 | 0.01 - 2.68 | 0 | 11 | 121 |
| 1979 | 43 | 0.005 - 0.637 | 0 | 22 | 134 |
| 1980 | 35 | 0.0067 - 2.66 | 0 | 11 | 120 |
| 1981 | 39 | 0.005 - 0.767 | 0 | 5 | 139 |
| 1977 to 1981 | 236 | 0.005 - 4.93 | 0 | 13 | 166 |
| Dissolved Phosphorus - Field Filtered (DPD) | | | | | |
| 1980 | 17 | 0.004 - 0.277 | 0 | 13 | 134 |
| 1981 | 30 | 0.0015 - 0.543 | 0 | 4 | 110 |
| 1977 to 1981 | 47 | 0.0015 - 0.543 | 0 | 6 | 134 |
| Dissolved Phosphorus - Lab Filtered (DPL) | | | | | |
| 1978 | 36 | 0.0013 - 0.32 | 0 | 5 | 50 |
| 1979 | 42 | 0.0015 - 0.227 | 0 | 3 | 62 |
| 1980 | 15 | 0.0015 - 0.05 | 0 | 17 | 44 |
| 1981 | 9 | 0.0015 - 0.0323 | 0 | 4 | 43 |
| 1977 to 1981 | 102 | 0.0013 - 0.32 | 0 | 4 | 62 |
| Ortho-Phosphorus - Field Filtered (OPD) | | | | | |
| 1981 | 10 | 0.0015 - 0.247 | 0 | 1 | 43 |
| Ortho-Phosphorus - Lab Filtered (OPL) | | | | | |
| 1977 | 1 | 0.0048 | 94 | 94 | 94 |
| 1978 | 7 | 0.0015 - 0.442 | 0 | 3 | 74 |
| 1979 | 4 | 0.0015 - 0.0363 | 0 | 2 | 78 |
| 1977 to 1981 | 12 | 0.0015 - 0.442 | 0 | 4 | 94 |
| Total Phosphorus (TP) | | | | | |
| 1977 | 242 | 0.0015 - 3.7 | 0 | 3 | 131 |
| 1978 | 71 | 0.0015 - 0.84 | 0 | 3 | 54 |
| 1979 | 43 | 0.0015 - 0.253 | 0 | 5 | 85 |
| 1980 | 31 | 0.0015 - 0.6 | 0 | 5 | 59 |
| 1981 | 38 | 0.0015 - 0.633 | 0 | 6 | 127 |
| 1977 to 1981 | 425 | 0.0015 - 3.7 | 0 | 3 | 131 |

parameters filtered in the field are at least as good as the corresponding lab filtered total precisions, while the two particulate parameters show poorer total precisions for the field filtered version. The maximum coefficients of variation for field filtered parameters are lower than their lab filtered counterparts with the exception of DOC and DP. It also appears tha POCL has shown some improvement in total precision during the last two years.

## DISCUSSION

The total precision of each parameter is estimated by the median of the coefficients of variation computed on all sets for that parameter. The total precision can be compared numerically to the analytical precision.

Table 4 summarizes the comparison of total to analytical precisions.

TABLE 4. Comparison of Total and Analytical Precision

| Parameter | Analytical Precision in % | Total Precision in % | Comparison |
|---|---|---|---|
| DOCL | 4 - 18 | 0 | BETTER |
| DICL | 2 | 1 | BETTER |
| NOD | 3 | 0 | BETTER |
| NOL | 0 - 4 | 3 | EQUAL |
| NH3 | 9 | 0 | BETTER |
| DND | 0 - 4 | 2 | EQUAL |
| DNL | 0 - 2 | 4 | POORER |
| DPD | 0 - 1 | 6 | POORER |
| DPL | 0 | 4 | POORER |
| OPD | 2 | 1 | BETTER |
| OPL | 0 | 4 | POORER |
| TP | 0 - 12 | 3 | EQUAL |

There are only four parameters, DNL, DPD, DPL and OPL, which show a total precision which is poorer (coefficient of variation greater) than the corresponding analytical precision.

However, this comparison is insufficient in terms of identifying problem parameters. The median coefficient of variation is only part of the story. By including maximum coefficient with the median coefficients, a two factor classification system can be set up. Fig. 1 depicts the system used. The boundaries were set somewhat arbitrarily and, therefore, the classification should be viewed as being indicative rather than definitive.

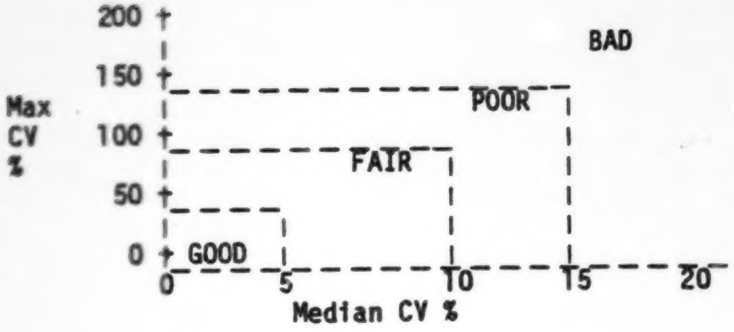

Fig. 1: Classification of total precisions.

Table 5 classifies each parameter according to the system depicted in Fig. 1. The parameters are evenly distributed among the four classes.

TABLE 5. Classification of Results

| Parameter | Median CV in % | Maximum CV in % | Class |
|---|---|---|---|
| TOC | 7 | 100 | FAIR |
| DOCD | 0 | 78 | FAIR |
| DOCL | 0 | 66 | FAIR |
| DICL | 1 | 31 | GOOD |
| POCF | 32 | 52 | BAD |
| POCL | 10 | 90 | FAIR |
| NOD | 0 | 71 | FAIR |
| NOL | 3 | 157 | BAD |
| NH3 | 0 | 43 | GOOD |
| DND | 2 | 16 | GOOD |
| DNL | 4 | 110 | POOR |
| PNF | 53 | 132 | BAD |
| PNL | 13 | 166 | BAD |
| DPD | 6 | 134 | POOR |
| DPL | 4 | 62 | FAIR |
| OPD | 1 | 43 | GOOD |
| OPL | 4 | 94 | FAIR |
| TP | 3 | 131 | POOR |

Total precision is a statistic and therefore has a distribution. This distribution could have a non-random component (Guilbault, 1981). As a first pass examination of this possibility, correlation coefficients for the coefficients of variation against selected independent variables were computed. Wilson (1976) and others have stated that the precision of measurement is dependent on the concentration, so, the mean concentration of the set was selected. River discharge was selected as an indicator of some of the in-stream processes which might contribute to the variance of the set. The last independent variable to be considered is transit time from the point of sampling to the laboratory. Inclusion of this variable was suggested by the work of V. T. Chacko (personal communication) on sample holding time for nutrient parameters.

Correlation coefficients were computed on sets grouped by fiscal year and by site. This produced 583 correlation coefficients of which 145 or 25% had a magnitude greater than 0.707 (determination greater than 50%). The grouping by site was indicated by previous work on particulate nutrient parameters (Guilbault, 1981) which showed that the relationship between the standard deviation and mean of a set for particulate nutrient parameters varied from site to site.

Although 25% of the coefficients of correlation are greater than 0.707, only about 2% of the groups consisting of 10 or more sets show coefficients greater than 0.707. There appears to be little correlation of precision to either mean concentration, river discharge or transit time to the laboratory. This is not to say, however, that there is no relationship between the variables, but simply that the relationship, if it exists, is not linear. Examination of the 20 sets with the worst CV's indicates that, although most of the anomalies are inexplicable, what evidence there is points to a wide variety of possible causes for poor precision. This relates back to the lack of correlation since large, random errors can mask a correlation even if the errors are of low frequency.

Guilbault (1981) also suggests that a more detailed examination of sets with large coefficients of variation can shed added light on the possible causes of poor precision. The 20 sets with the largest CV's were investigated in detail. The sampler's and analyst's notes and computations were reviewed for any evidence of a problem in handling the set. The corresponding non-filterable residue (suspended sediment) data, where available, were also examined.

Table 6 lists these sets and the results of the examination. Of the 20 sets, 14 were collected during fiscal year 1977, which pre-dates the introduction of computer assisted data verification in the laboratory. Fourteen are for the parameter Particulate Nitrogen - Lab Filtered (PNL) and 14 were collected from sites within the Province of Saskatchewan. The latter observation may be an artifact of the distribution of sites at which PNL is

TABLE 6: Twenty cases with the poorest precision

| CV | Parameter | Station | Date | Replicates | | | Remarks |
|---|---|---|---|---|---|---|---|
| 166 | PNL | 00SA06EA0003 | 20/12/77 | 0.005 | 0.05 | 1.8 | |
| 162 | PNL | 00SA05JM0014 | 21/12/77 | 0.005 | 0.1 | 2.3 | Lab noted 2.3 is "no good" |
| 159 | PNL | 00SA05FE0001 | 13/07/77 | 0.32 | 0.48 | 14. | |
| 159 | PNL | 00SA06EA0003 | 24/08/77 | 1.9 | 0.06 | 0.95 | |
| 157 | NOL | 00SA07MA0001 | 04/06/80 | 0.005 | 0.02 | 0.38 | NFR < 1. 1. 1. |
| 152 | NOL | 00AL05CK0001 | 17/07/79 | 0.11 | 0.005 | 0.005 | NFR 424 422 436 |
| 148 | PNL | 00SA05FE0001 | 16/08/77 | 1.5 | 0.08 | 0.08 | |
| 147 | PNL | 00SA05MD0002 | 23/11/77 | 0.09 | 0.005 | 0.005 | NFR 4. 6. 4. |
| 144 | PNL | 00SA05EF0001 | 14/12/77 | 0.08 | 0.005 | 0.005 | |
| 144 | NOL | 00NW06LC0001 | 14/07/81 | 0.005 | 0.005 | 0.08 | NFR < 1. < 1. 1. |
| 141 | PNL | 00AL05AK0001 | 13/12/77 | 0.005 | 0.005 | 0.07 | |
| 141 | PNL | 00SA05JM0014 | 24/11/77 | 0.07 | 0.005 | 0.005 | |
| 140 | PNL | 00SA05JM0014 | 25/08/77 | 0.54 | 7.4 | 0.54 | NFR 76. 78. 73. |
| 139 | PNL | 00AL07AA0023 | 21/04/81 | 0.005 | 0.1 | 0.01 | NFR 11. 11. 13. |
| 136 | PNL | 00SA05FE0001 | 18/10/77 | 0.005 | 0.06 | 0.005 | |
| 135 | PNL | 00SA05KH0002 | 22/11/77 | 0.005 | NV | 0.23 | Instrument failed to integrate second replicate |
| 134 | PNL | 00AL07GJ0001 | 11/06/79 | NV | 0.18 | 0.005 | NFR 23. 203 239 |
| 134 | DPD | 00AL05CK0001 | 10/06/80 | 0.009 | 0.1 | 0.009 | Typo - 0.1 should be 0.01 |
| 132 | PNF | 00SA05KH0002 | 20/09/77 | 0.13 | 0.005 | 0.02 | |
| 131 | TP | 00SA07LA0001 | 14/02/78 | 0.13 | 0.015 | 0.01 | NFR < 1. < 1. < 1. |

The results of the Field Quality Control Project, to date, point to a complex error distribution associated with the measurement of water quality parameters in the Western and Northern Region. The size of the tail of that distribution can impact detrimentally on certain kinds of water quality data interpretation. The large variances which are occasionally observed in time series of less than one hour in length could mask small but significant trends in longer, less frequently sampled series.

Data interpreters should be aware of the distribution of uncertainties in the measurement of water quality parameters in order to avoid potential problems. The data collector on the other hand must understand the distribution in order to control it in a cost effective manner. To control the uncertaininities in the measurements economically, quality control should concentrate on the most error-prone steps in the sampling and analysis procedures. In order to do this, all steps and the impact of errors at each step on the measurement must be identified.

## CONCLUSIONS

Only DICL, NH3, DND and OPD, of the 18 parameters studied show "good" precision by the criteria herein defined. The evaluation of precisions point to some seven problem parameters: POCF, NOL, DNL, PNF, PNL, DPD and TP.

The total precision cannot be tied to mean concentration, river discharge or time in transit between the point of sampling and the laboratory. The precision does not vary linearly with any of these.

Poor precision can be attributed to random errors, which can occur anywhere along the measurement process, from sample collection, through laboratory analysis, to data reporting.

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# A SUMMARY OF ANALYSES
# THE BRIDGER RANGE WINTER CLOUD SEEDING EXPERIMENT
# USING CONTROL GAUGES

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## ABSTRACT

A randomized cloud seeding experiment was carried out during the winters of 1968 through 1972 in southwestern Montana. Seeding was by ground-based AgI generators. Previous analyses of the data indicated a Type I error (illogical seeding signals were detected), casting doubt on the results. Recently developed statistical techniques using control precipitation gauges were applied to the data in a new analysis reported in this paper. The results suggest a seeding effect was present, yielding a 15 to 25% increase in snow pack for the final two years of the experiment.

## INTRODUCTION

The Bridger Range orographic cloud seeding experiment was conducted by researchers at Montana State University in the late 1960s and early 1970s. Their purpose was to test the hypothesis that the introduction of anthropogenic ice nucleants would enhance precipitation produced by winter-time orographic clouds. The Bridger Range experiment was one of a number of investigations of winter cloud seeding potential conducted in several states under the auspices of the Bureau of Reclamation's Project Skywater. This program was encouraged by apparent successes of the Climax I experiment reported by Grant and Mielke (1967) and Mielke et al. (1970).

Silver iodide was used as an ice nucleant and was released from one or two sites approximately halfway up the western slopes of the Bridger mountains for the three years discussed in this summary. The target was the Bangtail Ridge, approximately five to 20 km to the east of the crest of the Bridger Range. Fig. 1 shows a map of the area with seeding locations and the 31 weighing precipitation gauge network.

Several supporting investigations were carried out. These included airborne tracing of AgI plumes, airflow investigation, analysis of snow silver content, and attempts to directly detect the effects of short period seeding episodes through a variety of physical measurements. A complete description of this experiment is given in a two-volume final report by Super et al. (1972 and 1974), hereafter called Part I and Part II.

Analyses performed for Part II gave strong indications of Type I statistical error, i.e., some partitions yielded distribution of seeded and non-seeded days for which the statistical testing suggested changes in precipitation due to seeding when no logical cause and effect relationship was evident. Changes were for the most part in the sense that seeding apparently decreased precipitation.

Since the publication of Part I, statistical techniques have been developed which use control gauges to determine the natural trend, reducing the chances for Type I errors (Mielke et al., 1981a; 1982). These papers summarized the results of a reanalysis using these recently developed techniques. A full description is presented by Super and Heimbach (1983).

## PHYSICAL HYPOTHESIS AND EXPERIMENTAL DESIGN

The Bridger Range Experiment assumed that the abruptly rising Bridger range would provide strong uplift to moist eastward-flowing air, thereby producing liquid water condensate. It was further assumed that the concentration of natural ice nuclei and resulting ice particles were sometimes less than optimum for conversion of condensate to snowfall. This follows the proposed physical explanation of the climax statistical results (Grant et al., 1969), and these reflect the ideas in the classic paper by Ludlam (1955) as expanded by Chappel (1967) for the climax situation. The introduction of artificial ice nucleating material, AgI in this experiment, could therefore increase the efficiency of conversion of condensate to snowfall under certain conditions.

The experimental unit was 24 hrs, beginning at local noon, a known minimum in Bridger range winter precipitation. Experimental days were declared whenever a special forecast, issued each morning by the National Weather Service office at Helena, Montana, indicated the probability of precipitation at the Bozeman Airport exceeded 20% during the 24 hr beginning at noon.

The first attempts to seed clouds over the Bridger Range took place during the 1968-69 winter using AgI generators at two foothill locations at 1550 m, well below the 2600 m crestline. Measurements revealed the presence of a persistant stable layer during snowfall, implying no means for the AgI to be transported to the Main Ridge for most of the seeded periods. For the 1969-70 winter, one generator was operated two-thirds up the western slope of the Bridger Range and during the 1970-71 and 1971-72 winters this site and another site at a similar altitude were operated. For the last two winters, the AgI generators were among the highest output ground-based units tested at the CSU Simulation laboratory (Garvey, 1975), yielding approximately 6 X $10^{14}$ $gm^{-1}$ for natural draft and 2 X $10^{-16}$ for 10 $m.s^{-1}$ effective at -20'C. Each site burned 30 gm per hour. The last two years used a 3% (by weight) solution of AgI in acetone, complexed with $NH_4I$. During the 1969-70 winter, the single generator used a solution complexed with NaI. The clear difference in seeding material and source configuration imply that the last two years are distinct from the first two and, therefore, the bulk of the analyses presented in this paper are concerned only with the pooled sample of the 1970-71 and 1971-72 seasons. A total of 185 experimental units were derived from these two seasons, 90 of which were seeded.

Measurements taken in support of the experiment include 393 Rawinsonde observations (1680 mHz RD-65), temperature from two thermographs on top of the main Bridger ridge, airborne ice nucleus measurements, pilot balloon observations, silver concentrations in snow, and data from 31 continuously recording weighing bucket precipitation gauges.

## STATISTICAL TECHNIQUES

In the original analysis, the seeded and nonseeded absolute precipitation accumulations were compared using the Wilcoxon rank-sum and the squared-rank-sum tests (Noether, 1967).

Mielke et al. (1981a) introduced a nonparametric inference technique in a reanalysis of Climax I and II which reduced the possibility of Type I errors. In their study rank-ordered residuals from a linear least squares line, $y = bx$, fitted to paired target-control observations, were input to 2-sample rank-sum tests. This approach compensated for covariate data. However, Mielke et al. (1982) noted that the least squares inference can place undue weight on the outlying data pairs, and there is potential for distortion in the Wilcoxon rank-sum test due to its non-Euclidean geometry. A new nonparametric inference technique was developed and applied to the climax data to reduce distortions. Residuals were found using the median regression line, and testing was through multi-response permutation procedure (MRPP).

In this analysis both the well known Wilcoxan rank-sum test and the MRPP are used to test for differences in the rank-ordered target residuals determined from the median regression line. For this study the median regression line is forced through the origin to minimize the impact of "busted" forecasts and the number of cases when either the target or control, but not both, had 0 precipitation. The seeded and nonseeded target control pairs were pooled to define the median line. Only those pairs meeting partition criteria were applied.

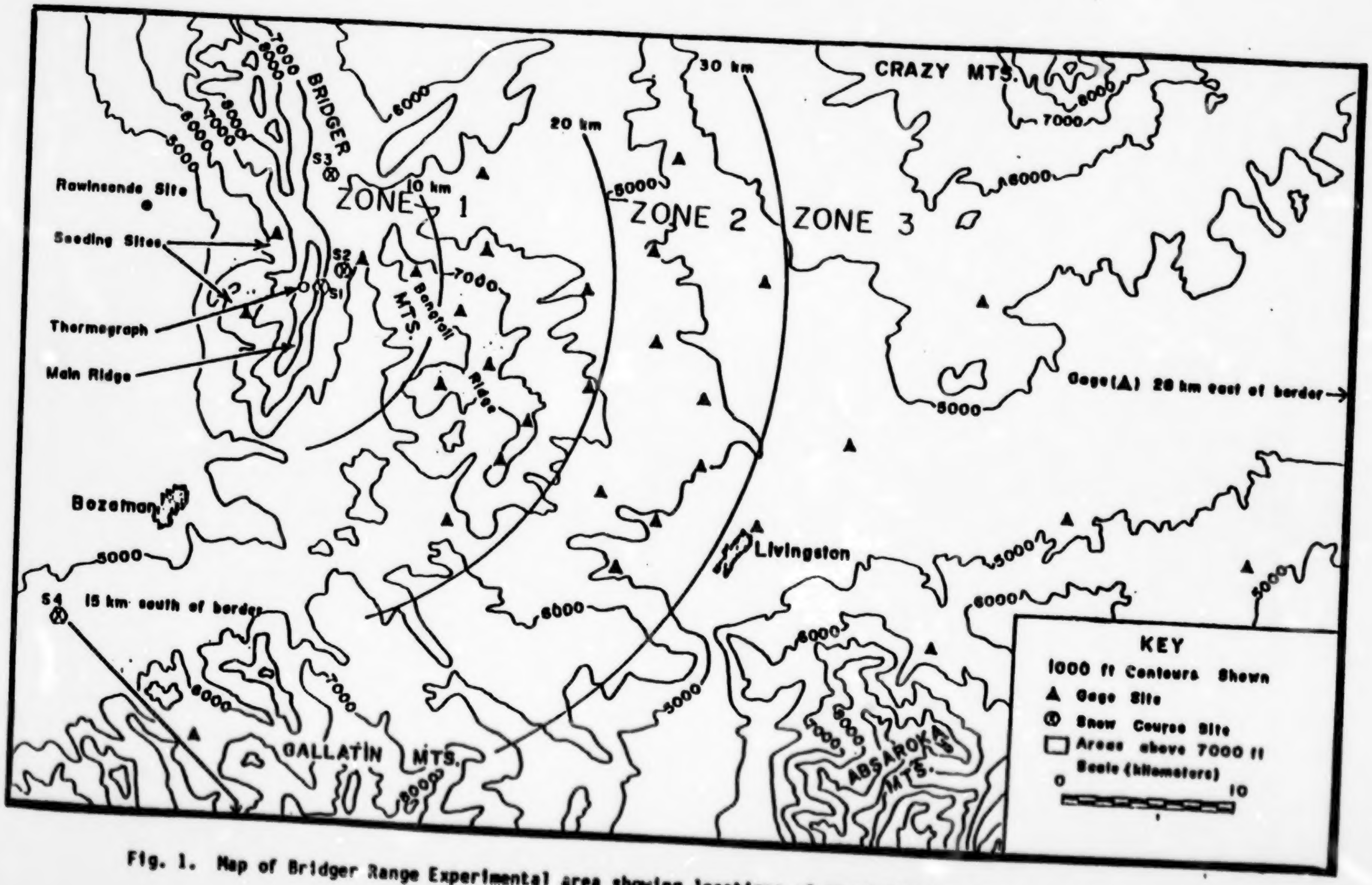

Fig. 1. Map of Bridger Range Experimental area showing locations of precipitation gauges and snow courses.

MRPP is described along with efficient computation techniques by Mielke et al. (1976), and an easily understood example is presented by Mielke et al. (1981b). For this study, there is only one response variable which is residual precipitation accumulation for the medians fit. The statistic, $\delta$, is found using the differences between the response variables to the unit power, i.e., Euclidean distance (k=1 of Mielke et al., 1976) is inferred. The effect of outlying residuals was minimized by substituting a score function for the residuals in MRPP. (See Mielke et al., 1982)

For the analyses presented in this paper, precipitation data were grouped into three zones. This was done by the simple expedient of averaging data from all gauges less than 20 km, from 20 to 30 km and beyond 30 km from the mid point between the two generator sites (see Fig. 1).

## RESULTS

### Partitioning by Meteorological Data

The precipitation data were partitioned by various meteorological parameters measured during the experiment. In the final analysis, 24 hr averages of these data were applied corresponding to the experimental unit. Partitioning included ridge top temperature, 700 mb temperature, 700 mb wind speed and direction, and cloud thickness (estimated from Rawinsonde data). Other partitions were examined but the results were inconclusive.

The must suggestive results came during periods when the near ridge temperatures were colder than about -9'C. Table 1 lists the probability levels for ridge top temperature partitions for the two statistical tests. Also shown are double ratios defined as:

$$\text{double ratio} = \frac{\text{seeded target/nonseeded target}}{\text{seeded control/nonseeded control}} \qquad (1)$$

This apparent increase was also found in partitions using the 700 mb temperature from radiosondes on the ridge top thermograph. The same trend was found using the two winters separately and also the 1969-70 winter which was not totally compatible with the last two.

Double ratios suggest that, on a seasonal basis, approximately 15% more snow fell during the seeded days in the intended target than predicted by the control gauge data. When the colder days were considered alone, double ratios suggested seeding associated snowfall increased of 50% or more.

The apparent increases in precipitation associated with seeding during the colder storms are believed consistent with current physical understanding, which admittedly still has serious limitations. The airflow and AgI plume tracing results from the BRE

Table 1. Summary of ridge temperature partitions. (Wilcoxson and MRPP one-tailed probability, and double ratios (D.R.) are for three zones of Fig. 1).

| | Cases | | Zone 1 | | | Zone 2 | | | Zone 3 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Range (°C) | All | S/NS | Wilc. | MRPP | D.R. | Wilc. | MRPP | D.R. | Wilc. | MRPP | D.R. |
| Part A - Fractions of all cases. | | | | | | | | | | | |
| -26.0/+ 5.0 | 185 | 90/95 | .17 | .22 | 1.15 | .35 | .36 | 1.05 | .12 | .12 | 1.13 |
| -9.4/+ 5.0 | 93 | 48/45 | .31 | .36 | .86 | .22 | .20 | .73 | .50 | .50 | .86 |
| -26.0/- 9.5 | 92 | 42/50 | .01 | .01 | 1.62 | .09 | .11 | 1.50 | .07 | .05 | 1.55 |
| -7.3/+ 5.0 | 62 | 29/33 | .33 | .34 | .82 | .42 | .50 | .85 | .45 | .50 | .99 |
| -11.5/- 7.4 | 61 | 32/29 | .30 | .41 | 1.18 | .10 | .11 | .76 | .34 | .21 | .84 |
| -26.0/-11.6 | 62 | 29/33 | .02 | .02 | 1.72 | .02 | .02 | 2.04 | .03 | .02 | 1.98 |
| -6.0/+ 5.0 | 47 | 22/25 | .33 | .36 | .89 | .33 | .30 | 1.38 | .26 | .24 | 2.03 |
| - 9.4/- 6.1 | 46 | 26/20 | .35 | .25 | .89 | .08 | .12 | .43 | .22 | .24 | .52 |
| -13.3/- 9.5 | 47 | 24/23 | .11 | .15 | 1.41 | .24 | .31 | .86 | .11 | .14 | .87 |
| -26.0/-13.4 | 45 | 18/27 | .01 | .01 | 1.86 | .01 | .02 | 2.96 | .01 | .01 | 3.19 |
| Part B - Colder cases by 2°C increments. | | | | | | | | | | | |
| -7.0 | 131 | 65/66 | .04 | .04 | 1.35 | .33 | .25 | 1.11 | .20 | .13 | 1.17 |
| -9.0 | 100 | 44/56 | .01 | .01 | 1.56 | .13 | .14 | 1.38 | .09 | .08 | 1.43 |
| -11.0 | 68 | 31/37 | .01 | .02 | 1.69 | .06 | .08 | 1.78 | .02 | .02 | 1.90 |
| -13.0 | 49 | 22/27 | .01 | .01 | 1.90 | .01 | .01 | 2.93 | .005 | .004 | 3.24 |
| -15.0 | 26 | 10/16 | .30 | .15 | 1.06 | .05 | .09 | 2.02 | .02 | .02 | 2.08 |

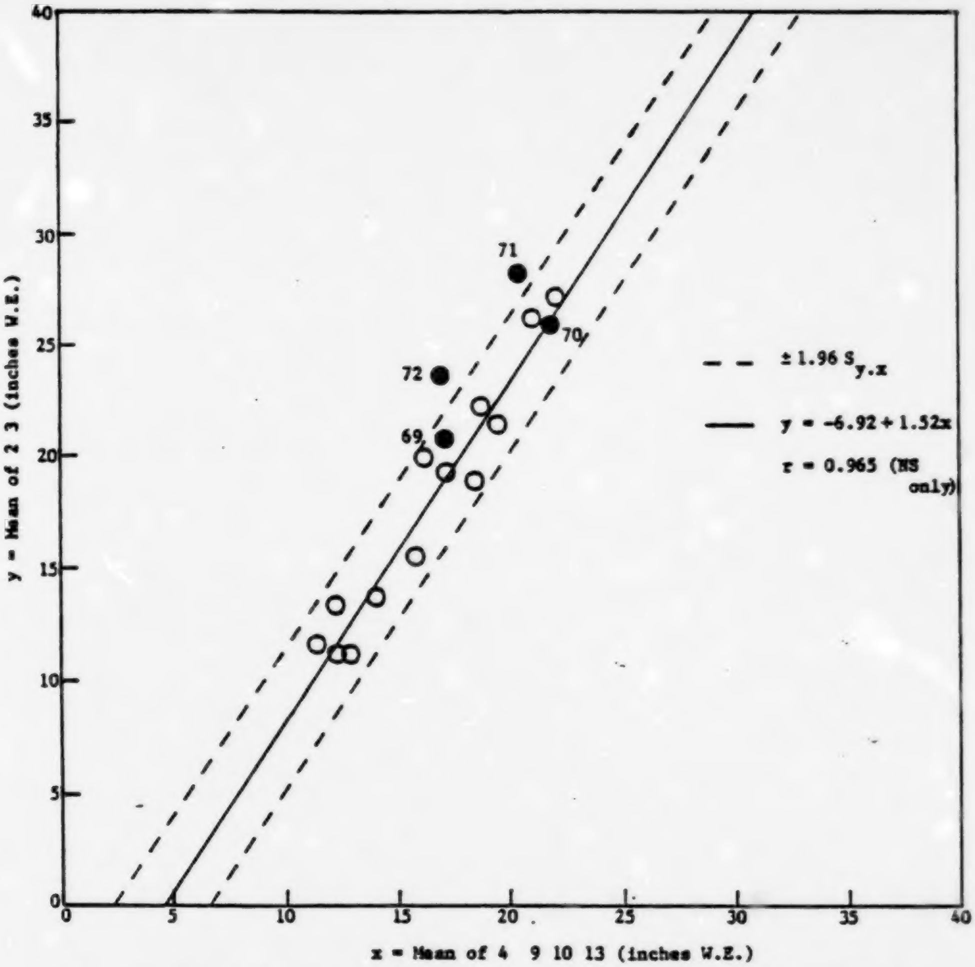

Fig. 2. Plot of March 1 snow course water equivalence: means of S1 and S2 vs S4, S9, S10 and S13. (Regression for 13 nonseeded winters. Data from 1967 through 1982.)

were reviewed. These are consistent with the hypothesis that the seeding agent generally was transported up and over the Main Ridge and toward the intended target, with sufficient diffusion for wide-area coverage by the AgI plumes. The strong uplift above the windward slope of the Main Ridge should have produced considerable condensate in the zone through which the AgI was transported. Further, simulation laboratory calibrations of the seeding generators used suggest that artificial nucleation should have been very limited until Ridge temperatures were colder than about -9'C.

## Supporting Evidence from Snow Courses

The Bridger Range experiment did not operate precipitation gauges on the east slope of the Main Ridge because it was assumed that small ice crystals formed just upwind of or over the Main Ridge would be carried well beyond this range. Analysis of the westernmost gauge (excluding control gauges) suggested an increase in precipitation, prompting an examination of the data from the two snow courses sampled by the Soil Conservation Service on the east slope of the Main Ridge (Bridger Bowl and Maynard Creek). Both are approximately east of the midpoint of the line joining the two seeding sites (S1 and S2 on Fig. 1). The two courses have continuous records since 1965 and 1967 respectively. March 1 data were used.

A search was made for other snow courses which would have a high correlation with the means of S1 and S2 but be removed from the influence of seeding. The highest correlation of 0.96 (excluding the four seed years) was with Sacajawea (S3 on Fig. 1) and Shower Falls (S4). Fig. 2 shows a plot of all points and a regression line fit to all but the seeded years. Plus an minus 1.96 residual errors are also plotted. Unusually high snowpack water equivalent values for the 1970-71 and 1971-72 seeded winter are indicated because values for these winters depart from the values predicted by control snowcourses by 16 and 20%, respectively.

## CONCLUSIONS

The Bridger Range Experiment was exploratory and the analyses were post hoc. The results, therefore, should be interpreted with caution due to multiplicity problems. The results, however, can be considered strongly suggestive.

The statistical analysis suggests that seeding increased snowfall in the intended target and sometimes further downwind as well when the temperature near the top of the Main Ridge was colder than about -9'C. This apparent increase was found in partitions using the 700 mb temperatures from radiosondes, or the temperatures measured by a thermograph at 2595 m elevation.

In the opinion of the authors, the results presented herein are encouraging enough to justify further field efforts in the Bridger Range. However, we would not advocate a confirmatory statistical experiment at this time. Rather, we would recommend a limited program of airborne measurements, primarily downwind of the southern generator site, as the most appropriate next step. Several plume tracing flights have shown that the southern generator site is capable of routinely producing AgI plumes that are transported over both the Main Ridge and Bangtail Ridge target area, with tops about 600 m above the highest point in the latter ridge. Preliminary contacts with the Federal Aviation Administration have suggested that it should be practical to make north-south aircraft passes above the Bangtail Ridge during storms, while within 300 m of the highest terrain. This would place the aircraft well into the seeding plume. An NCAR ice nucleus counter and repeated flight passes in opposite directions would delineate the seeding plume boundaries. Simultaneous measurements of liquid water content and ice particle concentrations and size spectra should yield marked differences between in-plume observations and those made crosswind of the plume. Analysis of such data, collected from several storms, should yield physical evidence that either tends to confirm or rejects the suggestion of the statistical analysis presented. If the airborne physical observations appeared in accord with the statistical suggestions, a confirmatory statistical experiment with a strong physical component would appear justified.

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## SYMPOSIUM:
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# INTERNATIONAL INTERBASIN TRANSFERS - A CURRENT ASSESSMENT

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## ABSTRACT

In the 1960s and early 1970s, a number of proposals for transfers of water from Canada to the United States were widely publicized. Most had very unfavourable features for Canada but some, with modifications, were more acceptable. The negative reactions engendered by NAWAPA especially made development unlikely but opposition within the United States was enough to put them on ice.

There is still frequent reference to the earlier proposals and the growing water demand patterns in some areas are resulting in renewed interest in transfer, some of it international in potential scale. Accordingly, we should assess the current potential for such transfer and note those trends that may contribute to or deter development. These range from the state of engineering technology for such development to environmental, economic, social, and political aspects and a wide range of conclusions may be reached.

## INTRODUCTION

As the only non-government person on the panel, I am better able to speculate and play the devil's advocate on aspects of the topic than others present. Hopefully, this will stimulate discussion and comment, and excite some additional thought and interest in the subject. I have been involved in this topic for almost 20 years, including all of one sabbatical year and parts of two others; I have commented on it on numerous occasions, including in some 25 published papers, I have run several conferences on it - and I am about as uncertain concerning where we are going on it as anyone in the room.

## BACKGROUND - INTER-REGIONAL DIVERSION

In the 1960s, proposals for international interbasin transfers grew out of lesser scale transfer proposals within the United States, Canada and Mexico, and from dire water use projections that indicated imminent shortages. The proposals were largely related to growing urban, industrial, irrigation and other demands in the Southern California - Lower Colorado Basin Region, the High Plains, especially in Texas, and to a lesser extent in Eastern Colorado and Utah. The City of Los Angeles and, later, the Metropolitan Water District of Southern California, with a rapidly rising income from a growing property tax base, had imported water incrementally from the Owens Valley and the Colorado River, and was planning to import Northern California water. The California State Water Plan and the central Vallay Project of the Federal Government were under way. By Supreme Court decision in 1965, Arizona won its right to enough water from the Colorado River for its Central Arizona Project, partly at the expense of Southern California, which put pressure upon the latter to look elsewhere for its supplies. In Colorado, at least 11 transfers were operating and planned to move Upper Colorado Basin water through the Continental Divide to the Eastern slope for use in urban development and in irrigation projects. Similar transfers from the Colorado Basin were developed and being developed in Utah. The Texas Water Plan was being formulated - it narrowly lost in a plebicite in 1969 because East Texas wasn't willing to give up its water for West Texas use without assured replacement supplies from the Mississippi or other sources. Other plans for transfers to take the place of and supplement the depleting supplies in the Ogalalla Aquifer were being outlined. A significant feature of these plans was that all of those developed were within individual states -there was no interstate development, and there was very little detailed planning at an interstate level. A number of interstate transfer proposals were promoted by Bureau of Reclamation personnel, private consultants and others (Table 1), but none of them got past the proposal stage.

TABLE 1. Interregional diversion proposals

| Proposal | Year | Volume (million $dam^3$) | Estimate Cost ($billions) |
|---|---|---|---|
| Pac.SW. Water Plan (Interior Dept.) | 1963 | 148 | ? |
| Western Water Project (Pirkey) | 1963 | 16.03 | 12.8 |
| Sierra-Cascade Project (Miller) | 1963 | 9.2-37 | ? |
| Snake-Colorado Project (Nelson) | 1963 | 3.0 | 1.4 |
| Modified Snake-Colo. Project (Dunn) | 1964 | 6.2 | 3.6 |
| Yellowstone-Snake-Green Project (Statson) | 1964 | 2.5 | 0.4 |
| Undersea Coastal Aqueduct (NESCO) | 1965 | 13.6 | 8.0 |
| Undersea Hose (Conner) | 1967 | 14.8 | 2.0 |
| Great Plains Plan (Beck) | 1967-8 | 12.3 | 3.5 |
| Hudson Institute Plan (Hudson Inst.) | 1968 | 41.9 | 12.2 |
| Texas Water Plan (State of Texas) | 1968 | 21.0 | 9.0 |

(From Quinn, 1973, p. 16)

Canadian interbasin transfers had been largely for hydro power production by the early 1970s and, at that stage, Canada had a bit greater volume of diversion than the United States. In recent years, this has expanded rapidly with the James Bay, Churchill-Nelson and other projects, and we now have interbasin transfers of about 90 million acre feet or 111 million dam$^3$ per year - about seven times as much as the United States. Transfers for irrigation, urban and other purposes are a relatively small part of this total, possibly one to two percent. The transfers included are from the Bow River into the Red Deer and Oldman basins in the Eastern, Western and Bow River Irrigations Projects, and from the South Saskatchewan into the Qu'Appelle for urban, recreational, irrigation and other purposes. Others have been proposed: from the North Saskatchewan and Red Deer in the Pearce Plan, with later changes by PFRA engineers; from the Assiniboine to serve the Lake Agassiz Plain south-west of Winnipeg; and from the Shushwap to supplement supplies in the Okanagan. There is no scheduled development time for any of these. Perhaps the main projects of wider interest were the PRIME (Prairie Rivers Improvement, Management and Evaluation) program in Alberta, and the Saskatchewan-Nelson Basin Board studies in much of the southern prairie. The PRIME program of the Social Credit Government in Alberta from 1965 to 1971 was to plan for the sequential transfer of northern Alberta water southward as needed, with replacement supply from still farther north assured to those basins initially giving up water for southern use. This program died with the election of the Conservative Government in 1971 but, as will be noted later, the plan has been resurrected in the last three years. The Saskatchewan-Nelson Basin Board studies of possible storage and transfer in the Prairies concluded in 1972 that the potential for both was large, at relatively low cost, but, major conclusions and recommendations should await the completion of demand and environmental studies. Some of the latter have been completed recently, but most conclusions are being left for the provincial governments involved. Neither PRIME nor the Saskatchewan-Nelson Basin Board studies were export-oriented, but in both it was shown how substantial amounts of water could be moved to near-border areas.

## INTERNATIONAL DIVERSION

The American proposals, especially, set the stage for more ambitious proposals involving transfer across international borders, mostly from Canada to the United States, but some involving Alaska and/or Mexico (Table 2). These were much more widely publicized, especially the NAWAPA scheme of the Ralph M. Parsons Co. of Los Angeles (now of Pasadena).

The North American Water and Power Alliance (NAWAPA) proposal would involve the transfer southward of over $10^8$ dam$^3$ of water per year (about seven times the flow of the Colorado or Saskatchewan or Yellowstone Rivers), largely from Western Canada, Alaska and the Pacific Northwest, and largely to the American Southwest from

TABLE 2. International diversion proposals

| Proposal | Year | Volume (million dam$^3$) | Estimate Cost ($billions) |
|---|---|---|---|
| Grand Canal Plan (Kierans) | 1959 | ? | ? |
| Great Lakes-Pacific Waterways Plan (Decker) | 1963 | 142 | ? |
| North America Water and Power Alliance or NAWAPA (Parsons) | 1964 | 136 | 100 |
| Magnum Plan (Magnusson) | 1965 | 31 at border | ? |
| Kuiper Plan (Kuiper) | 1967 | 184 | 50 |
| Central North American Water Project or CeNAWP (Tinney) | 1967 | 184 | 30-50 |
| Western States Water Augmentation Concept (Smith) | 1968 | 49 at border | 90 |
| NAWAPA-MUSHEC or Mexican-United States Hydroelectric Commission (Parsons) | 1968 | 194 & 159 | ? |
| North American Waters, A Master Plan or NAWAMP (Tweed) | 1968 | 1849 | ? |

(From Quinn, 1973, p. 16)

California to Texas. It would be run by a supra-national organization (NAWAPA) which would control much of the water, land and energy resources of the source regions. The proposal was promoted widely by the Parsons Co., by Senator Moss and his Senate committee, and by others intrigued by the massive scale and potential of the scheme.

The Magnusson proposal was made by a Canadian who saw potential for a large and easy transfer via a system of natural spillway channels across the prairies to the Missouri Basin. Ed Kuiper, of the University of Manitoba, visualized a different routing via Manitoba into the Missouri Basin for water surpluses from the northern prairies, with a sales price of $40.00 (Canadian) per dam$^2$ at the border. Roy Tinney, a Canadian who was then Director of the Water Resources Center at Washington State, expanded on the Kuiper scheme with plans for water movement into the Texas High Plains and westward to the Lower Colorado Basin. Lewis Gordy Smith, formerly with the Bureau of Reclamation, proposed moving water from the Mackenzie Basin (at 152 m elevation) southward via the Rocky Mountain Trench to the Centennial Valley, west of Yellowstone Park (at over 2134 m elevation), and letting it fan out from there to serve much of the Western United States. These were the main proposals, but there were others which had interesting features. One was by William Ackermann, Director of the Illinois Water Survey, who suggested that the Chicago diversion from Lake Michigan be expanded, and that other cities on Lake Michigan, Lake Huron and Lake Erie send their treated wastes southward to the Gulf of Mexico, thereby reducing the pollution problem in the Great Lakes. Additional fresh water for reservoir enhancement, urban, and industrial uses might be diverted, and a replacement supply could then be diverted from James Bay river basins into Lake Superior, adding to the present Ogoki and Long Lac diversions. An interesting feature of this proposal was that the extra flow in the Mississippi system could be available for transfer to Texas and other High Plains states. Other proposals (Jensen and Ellis, 1967) were for products pipelines to be built from prairie areas to carry items such as grains, sulfur, oil products, and wood chips in suspension, solution, and/or pellets to markets such as Los Angeles or Chicago, where the medium (water) could also be sold. It was also suggested that irrigation project development in the prairies and the interior of British Columbia could include transfer for sale in the United States and benefit from economies of scale and in other ways.

There were two important reasons for interest in the international proposals. First, there was the apparent availability of large unallocated water supplies. Secondly, people in potential basins of origin within the United States, who objected to their future supplies being committed for use elsewhere, with little or no benefit to them, and with them sharing the costs of transfer, were opposed to the projects. In addition, it seemed likely that the costs of transferring "new" water the greater distances might not be as great as the legal and other costs of re-allocating "old" water within the country. Engineering proposals with little or no provision for minimizing environmental damage, providing little compensating environmental enhancement, were fair game for blanket condemnation by American environmentalists. Some promoters thought that damage in other countries would not excite similar objections in the United States because water was considered to be a free good, and payment for water beyond the costs of transfer was not considered in the earlier proposals, such as NAWAPA. Some of the promoters believed that the multiplier effect of all of the proposed new engineering development was adequate compensation to Canada and that they, as developers, should be welcomed with open arms.

They were not!

When Canadians (including politicians) realized that the NAWAPA proposal, if developed, would result in many of British Columbia and Yukon valleys being flooded, such cities as Prince George and Whitehorse being submerged, and that major dams along active fault zones could constitute major hazards, they reacted negatively. The navigation benefits claimed were illusory because the canal system was designed for water transfer and power development. Thus, in terms of traffic potential, the canals led from nowhere to nowhere, and they would be icebound much of the year. The areas proposed for irrigation development could be irrigated more cheaply from local Canadian sources, and there were few, if any, economies of scale for Canada in these proposals. There is no doubt that promoters trying to sell their schemes in Western

United States and in Washington failed in their public relations efforts to convince Canadians of the projects' usefulness. Many Canadians, interested in the broader concept and in development that might be mutually beneficial, suggested that water should be sold by Canadians at a price sufficient to cover environmental and development costs and that there should be a profit. They suggested also that sales agreements should be terminable by either side, over a time period, if mutually beneficial arrangements could not be maintained. Environmental enhancement should be a major part of the cost of development, not something that could be ignored because the development was to be in a foreign country. By the early 1970s the negative reactions engendered by earlier proposals, including NAWAPA's, were so strong that most discussion of mutually beneficial programs fell on deaf ears and all of the proposals were condemned.

In the emotion-charged atmosphere that was developing, it is probably best that formal international negotiations were not started and that opposition within the United States was sufficient to put the schemes on ice. The Jackson Amendment to the Central Arizona Project Act in 1967, by which a ten-year moratorium was placed on U.S. Federal Government involvement in studies and development of transfer to the Colorado Basin, greatly reduced speculative promotion. The coalition of Northwestern basin-of-origin legislators in Congress, with others disturbed by the potential environmental costs and economic subsidies involved, had stopped activity long enough for re-evaluation and more careful assessment. The slow-down wasn't immediate: the Western States Water Council and other agencies continued discussions for some years and many of the more positive features were outlined in the period from 1967 to 1972. To a growing degree the conclusions reached were negative. Roy Tinney, in outlining CeNAWP as a cheaper way of moving water southward than NAWAPA concluded that no way was really feasible.

The dire predictions of water shortages, so prevalent in the 1960s (Piper, 1965) were modified in the 1970s. Studies by the Water Resources Council and other agencies, which differentiated between withdrawal and consumptive use, were helpful because they pointed out that recycled water from urban, industrial, thermal power and other users was available for re-use downstream. Many firms, whose costs were increased by pollution controls, found that re-cycling water was less expensive than treating water which had been used only once. More recent projections reflect these and other changes, such as the growing use of cooling ponds, cooling towers, and salt water in thermal power plants. They also reflect a growing acceptance of declining irrigation activity in areas of depleting ground water supplies, such as the High Plains - Ogallala region. Withdrawal uses in the United States (Table 3) involved 27.4 percent of the streamflow in 1975 and consumption was only 8.5 percent. Growth in use is anticipated, and the drier regions will have increasing problems of meeting demands, even with conservation measures. Much of the expansion in irrigation will be in sub-humid to humid regions where supplies are still

Table 3. Withdrawals and consumption use - Canada and United States - fresh water* (million cubic metres per day)

| Withdrawals | Total MCMD | Municipal MCMD | Manufacturing MCMD | Mining MCMD | Agriculture MCMD | Thermal MCMD |
|---|---|---|---|---|---|---|
| Canada 1974 | 16.6 | 2.0 | 5.7 | 0.6 | 1.6 | 6.5 |
| Canada 1980 | 32.0[a] | 3.2 | 10.3[b] | 1.2[c] | 2.2 | 15.1 |
| United States 1965 | 269.6 | 23.7 | 46.5 | 3.2 | 112.6 | 62.7 |
| United States 1975 | 338.5 | 26.7 | 51.2 | 7.1 | 160.7 | 88.9 |
| U.S. 2000 (1968 est.) | 593.4 | 50.7 | 127.4 | 33.0 | 153.2 | 259.2 |
| U.S. 2000 (1978 est.) | 306.4 | 34.7 | 19.7 | 11.3 | 156.4 | 79.5 |

| Consumption | Total MCMD | Municipal MCMD | Manufacturing MCMD | Mining MCMD | Agriculture MCMD | Thermal MCMD |
|---|---|---|---|---|---|---|
| Canada 1974 | 1.8 | 0.1 | 0.24 | 0.32 | 0.85 | 0.27 |
| Canada 1980 | 2.82 | 0.53 | 0.41 | 0.60[f] | 1.17[g] | 0.11 |
| United States 1965 | 77.8 | 5.2 | 3.8 | 0.8 | 66.3 | 0.8 |
| United States 1975 | 105.4 | 6.1 | 6.1 | 2.2 | 88.3 | 1.4 |
| U.S. 2000 (1968 est.) | 126.2 | 16.5 | 10.0 | 1.4 | 93.0 | 4.6 |
| U.S. 2000 (1978 est.) | 135.1 | 8.0 | 14.7 | 3.6 | 95.1 | 10.5 |

Canada - annual streamflow - 11,070 MCMD[d]
United States (48 states) - 5,600 MCMD[e]
United States (50 states) - 9,148 MCMD

* Based upon data from Environment Canada and the United States Water Resources Council, First and Second National Assessments.

a) The gross demand was 220 but with re-circulation this was reduced to 145.
b) The gross demand was 108 in manufacturing but with re-circulation this was reduced to 47.
c) The gross demand was 20 in mining.
d) In 1980, Canadian withdrawals were 1.31% and consumption 0.12%.
e) In 1975, American withdrawals were 27.4% and consumption 8.55%.
f) The greater part of this was for secondary recovery of oil and gas, largely in Alberta.
g) In 1978, a relatively dry year, the consumptive use for irrigation was 7.7 including Alberta 5.5, Saskatchewan 0.7 and Manitoba 0.05. In that year, consumptive use in Alberta was over half of that of Canada.

there is no reasonable prospect that any other plan for transporting Mississippi River water to west Texas and eastern New Mexico would have a favorable ratio of primary benefits to costs...." (p. 156). The Office of Management and Budget in the United States and the Treasury Board in Canada do not include secondary benefits. In 1980, Dr. Kazmann, at Louisiana State University, suggested that because of greatly increased energy costs, the ratio of 1973 would then be far worse.

General Hugh Robinson, U.S. Army Corps of Engineers, reporting on water importation feasibility to the High Plains Study Council in March 1982, noted that the cost of importing water to the High Plains-Ogallala study would range from \$279 to \$702 (US) per dam$^3$ (in 1977 dollars). This would not include farm delivery costs and environmental and other costs, and permission to collect water in the proposed source in Arkansas had not been obtained. The Arkansas legislature passed an Act by which export of water in units larger than a bucket was prohibited. The transfer options were accordingly given less stress in the study than ways of conserving and fully using what was available, and ways of converting back from irrigation to dry farming. The acceptance of a reversion to dry farming is by no means complete, and political pressure will continue to be exerted for transfers into the region. Howe and Easter (1971) had considered rescue operations to support existing development to be more feasible than the development of a new regional economy. The failure of the High Plains-Ogallala region to get national support for transfer (to date at least) would indicate a hardening attitude that the beneficiary region should pay most, if not all, of the large costs of transfer.

The farmers who are the direct beneficiaries of project development have not paid the greater part of the costs of many irrigation project developments in the past. In a recent Resources for the Future publication, Frederick and Hanson (1982), reporting on several studies, noted that the federal subsidy for 18 irrigation districts studied had ranged from 57 to 97 percent of the full cost and up to \$4413 (US) (p. 68 & 69). Of the \$3.62 billion spent by the Bureau of Reclamation on irrigation construction, 56.7 percent has been and will be paid from electricity sales, 40 percent from general tax revenues, and only 3.3 percent by farmers (p. 68).

A large part of the irrigation expansion in the last few decades has been in private ventures, largely with centre pivot equipment, and subsidies have been small. Much of this expansion is in sub-humid regions using relatively cheap, local water supplies. Perhaps if irrigation expansion is needed, this is the better way to go, rather than trying to import expensive water into the drier regions. It can probably be shown that project irrigation is one of the more expensive ways of increasing agricultural production.

In Canada, as noted earlier, there has been major interbasin transfer for hydro power development and very little in recent years oriented to irrigation and multiple purpose projects. The anti-export attitudes have carried over to internal transfer proposals and studies such as one by Hutton and Black (1975) in Northern Ontario. In part, this was started to investigate advantages and disadvantages of transfers into Lake Superior, but it ignored most of the subject and concluded that the integrity of natural streams should be preserved.

In 1979, Henry Kroeger, Minister of Transportation in the Alberta Cabinet, formed a committee to study transfer, partly to his constituency which is dry with very little irrigation. A consultant for the committee, formerly active in the pre-1971 PRIME program, prepared a report recommending that 22 million $dam^3$ of water should be transferred from the Peace River to irrigate 2.4 million hectares in southern Alberta. The rationale for this recommendation was that the irrigated land could be put into production to alleviate world food shortages. Even in drier years, this is more than twice as much water as could be used by such an area and the costs and problems of irrigating some of these lands as well as those of transfer could be very large. Consultation with environmentalists was invited and the cost aspects were largely ignored on the assumption that there was plenty of money in the Alberta Heritage Fund to cover them. It was assumed that all transfer costs would be borne by the province and that the irrigation districts should cover 14 percent of local distribution costs for ditches of up to 2 cfs capacity. The level of subsidy involved, possibly 98 to 99 percent, would exceed that for any district in the United States. Mr. Kroeger, now Chairman of the Alberta Water Resources Commission, might well be prepared to compromise on many issues if it could help to get things moving. The change in approach is abrupt and the government's official position has not yet been changed, but there is obviously strong Cabinet support for transfer within Alberta. If compromise positions could involve much smaller scale and sequential transfer, with a minimum of environmental damage, compensating enhancement, and better integrated water and related land-use planning, the confrontations now apparently developing might be greatly reduced. At present in Alberta, however, confrontation and gung-ho development are probably good politics. There may be other issues that could affect this program - among them the downturn in the economy, other outlets for Heritage Fund monies, interest in power development on the Slave River, federal confrontations over energy policies, and medicare - so forecasting can be very difficult.

## CONCLUSION

We might hope, as professionals, that interbasin transfers, including international transfers, might be studied rationally and objectively, and that reasonable alternatives could be outlined for public review and political decision-making. We might wish that development might take place with more than engineering structures planning; that environmental and social and economic aspects would receive due consideration; and that nationalism and emotional issues could be subordinated. Unfortunately, the trends in recent years in both Canada and the United States are not encouraging. We will probably not see much international, interprovincial, or interstate transfer for irrigation, partly because of good and valid economic, environmental, and other reasons, but mostly because of nationalism, emotion, and political agreement difficulties. We will probably see much more transfer for irrigation within provinces and states, often without good and valid reasons, and for too many of the wrong reasons. And in the very long run, will it matter much if the reasons are valid or not? As professionals, we must believe it does matter and we will have to keep plugging away, doing the best job we can.

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# COOPERATION AND CONCERNS, FLATHEAD RIVER BASIN MONTANA AND BRITISH COLUMBIA

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## ABSTRACT

The Flathead River Basin in northwest Montana and extreme southeastern British Columbia is an area being managed with opposing objectives. While Montana and the United States have increasingly recognized conservation, British Columbia has viewed this area as an important area for increased resource development. The proposed Cabin Creek coal mine has brought this situation to a head. Information exchanges undertaken in 1980 have provided a mechanism to establish a dialogue between Montana and British Columbia concerning this area. Although information exchanges will not necessarily resolve the difference between environmental management on both sides of the border, they have acted as a forum to move in this direction. Information exchanges have been very successful in providing a means to conduct nonadversarial discussions which allow for informal local input, facilitate the flow of information, make each other aware of respective resource management processes and long-term objectives. Lessons learned from the Flathead information exchanges indicate that these exchanges could be useful in assisting in the resolution of other transboundary disputes.

The Flathead River Basin in northwestern Montana is an area with unique natural resources long recognized in the United States for its high quality and scenic beauty. Situated at the headwaters of the Columbia River drainage, the Flathead River begins at an apex where water separates into three major drainages of North America, flowing north to Hudson Bay, east to the Atlantic Ocean, and west to the Pacific Ocean. Located within the United States portion of the basin are nationally recognized areas such as Glacier National Park, a designated World Biosphere and a component of an International Peace Park; the Bob Marshall, Great Bear, Mission Mountains and Confederated Salish and Kootenai Tribal wilderness areas; the Middle, North and South forks of the Flathead River, designated components of the National Wild, Scenic and Recreational River System; and at the heart of the basin, Flathead Lake, classified oligo-mesotrophic and the largest natural lake in the western United States. Due to its location in the drainage, Flathead Lake acts as a catchment reflecting the management of the basin's resources. Timber harvesting, agricultural, metal refining and tourism dominate the economy of the region. These oftentimes conflicting land uses have managed to coexist within strict conservation objectives within the United States portion of the drainage.

The northernmost portion of the basin, comprising approximately five percent of the land area, is situated in extreme southeastern British Columbia. Unlike the United States and Montana, where conservation has been increasingly recognized, Canada and British Columbia viewed the Flathead as a rich resource. Located far from population centres within an area rich in extractable natural resources such as coal, gas and oil, and other minerals, as well as vast timber resources, British Columbia has considered this area to be important for economic expansion. The decade of the 1970s has seen interest in timber harvesting, coal development and petroleum exploration soar.

Although there were concerns about all resource development, the prospect of open-pit coal development brought that issue to the fore. Absent from the United States portion of the basin, remenant coal deposits are found throughout the Canadian portion of the drainage. Coal mining within the Crowsnest Coalfield, an area extending from the international border north for approximately 160 km, has been ongoing since 1898. During the 70 years after 1898, coal extraction remained relatively static at approximately one million tons of coal per year being mined entirely through underground methods. Although still confined solely to the Elk River drainage, a tributary to the Kootenai River, by 1975 coal extraction had expanded thirteenfold, largely through open-pit mining methods. While development has continued to occur within the Elk River drainage, interest in Flathead River basin coal deposits increased significantly during the decade of the 1970s. Preliminary coal exploration has occurred at five sites throughout the drainage. One of those sites, the proposed Cabin Creek coal mine, continues to move forward.

The presence of coal in the North Fork River valley was first noted in 1910 and was referenced in the Geological Survey of Canada, Memoir 87, published in 1916. Serious attempts to develop this coal began in the late 1960s when the predecessor to Pan Ocean Oil Ltd., which has since been acquired by Aberford Oil Ltd., obtained coal leases in the vicinity of Cabin Creek. A new company, Sage Creek Coal Company Limited was formed in September 1970, 60 percent owned by Rio Algom Limited and 40 percent by Aberford Oil Limited, to explore and develop this property. Exploration and mine development planning have continued until the present. Exploration has identified approximately 152 million tonnes of coal in place. The coal found at the proposed mine site is soft, friable, of bituminous rank and volatile matter, 25 to 35 percent ash, and one-half percent sulphur, coal qualities highly sought after in today's world. Current mine plans call for the development of a thermal coal mine utilizing twin open-pits, each approximately 1.6 km across with a production rate of 2 million tonnes of medium volatile clean coal annually over a 21 year mine life. Mine development will include a processing plant, coal dryer, tailings ponds, waste dumps and ancillary facilities. Clean coal will be transported by truck 66 km over an upgraded 34m wide road to Morrissey where it will be transhipped by rail to the coast. Power will be supplied through construction of a 230 kv transmission line from Natal in the Elk River valley.

## MONTANA'S CONCERNS

The policy of expanding conservation objectives within the Montana portion of the drainage coupled with British Columbia's desires for expanding resource development set the stage for confrontation. Although a decison as to whether the mine will move forward is expected sometime this summer, confrontation has been replaced in favor of coordination and cooperation. Information exchanges instituted in 1979 have provided a basis for this ongoing dialogue. By emphasizing scientifically gathered data over emotionally charged arguments, a basis has been established for a non-confrontational dialogue. The Cabin Creek issue may still arrive at an impasse, forcing either or both parties to seek higher levels of redress; but in arriving at this impasse, the issues will have been narrowed to the Flathead River drainage and each will have a clearer understanding of the other's concerns. We will be friends coming to a table to disagree rather than unknown adversaries coming to do battle. This foundation of relying upon commonality rather than differences will hopefully provide for the resolution of the North Fork Flathead River Basin issues. Even if the information exchanges and communication were to terminate immediately, they would have been successful. It is this type of dialogue which can be used as a tool or a model to assist in resolving many of our border issues. In order to gain a better understanding of this tool, let us review the background surrounding interaction between British Columbia and Montana concerning a Cabin Creek coal mine.

Montanans first became alarmed over the prospects of an open-pit coal mine through an article which appeared in the September, 1974 issue of Montana Outdoors. The Flathead valley is considered to be a special area in the eyes of Montanans, and a huge "hue and cry" of concern arose following this article. Mounting anxiety led to the formation of a group calling themselves the Flathead Coalition. This group, comprised of conservation, wilderness, and recreation interests, chambers of commerce, and the League of Women Voters, began to press for governmental action.

Reluctance on the part of British Columbia to discuss the issue first surfaced in February of 1975, when a senior reclamation official in the Ministry of Energy, Mines and Petroleum Resources declined an invitation from former Governor Tom Judge to discuss the Cabin Creek problem. Although J. D. McDonald had initially expressed an interest in attending a meeting with

Governor Judge, the provincial government felt that a meeting would be premature. That same spring, former Representative Max Baucus made a special trip to Toronto to discuss the mine plans with the parent company, Rio Algom. Following this meeting, and after receiving vague assurances from the company, Representative Baucus pushed for consultations between the Canadian Ministry of External Affairs and the U.S. State Department. Late in October 1975, the U.S. State Department honored Representative Baucus's request, forwarding a diplomatic note to the Canadian embassy.

This note resulted in consultations being held on 9 March 1976. Recognizing that mine proposals were extremely tentative, British Columbia offered to provide detailed environmental impact studies to both Montana and the State Department for their input. The possibility of future consultations was left open. Concerns continued as mine planning moved forward but governmental interaction between Montana and British Columbia was minimal.

With Stage I or preliminary approval in hand, Sage Creek Coal Company began data collection in preparation of the Stage II or detailed environmental assessment. To date all interactions between Montana and British Columbia had occurred at a very high policy level. The burden had clearly been placed on Montana's shoulders to state its case.

It became apparent that solid baseline data and an understanding of the interconnectedness of the Flathead ecosystem would be critical to Montana successfully expressing its concerns. Through the efforts of Representative Baucus, the U.S. Congress authorized the undertaking of a five-year $2.9 million Flathead River Basin Environmental Impact Study. Undertaken in 1978, this study was completed in June of this year. The study, directed by a local Steering Committee, has been able to gain a "state of the art" understanding of the aquatic ecosystem and air resources of the Flathead River Basin. The study clearly demonstrated that 10 percent of the bull trout spawning for the entire approximately 21,000 $km^2$ drainage occurs along 2.4 km of stream directly adjacent to the mine site. Thus 10 percent of the bull trout fishery could be lost in Flathead Lake through the development of the Cabin Creek coal mine. Studies were also undertaken investigating: water quality, benthos, air resources, and wildlife. A solid ecological baseline was being established.

The Steering Committee in 1979 became increasingly concerned that as mine development planning moved ahead, plans based on company-generated data would begin to foreclose future development options. These data collected directly at the proposed mine site could differ considerably from data collected throughout the entire region. Further, data collected in the Montana portion of the drainage could be important to British Columbia agencies in determining what needed to be investigated by the company, and how the company's data should be interpreted.

Further, an increasing concern of the Steering Committee was the fact that Montana and United States officials, as well as citizens, continued to feel uncomfortable with British Columbia's seeming lack of specific standards. Unlike the United States, where regulatory law is extremely well defined and standards for both denial and approval have been clearly spelled out, Canada and British Columbia rely to a much greater extent upon governmental discretion. Although British Columbia has a well-conceived process for approving new coal mines, it lacks the types of standards that we have learned to expect. Montanans, who had adopted some of the most stringent coal mining standards in the country, felt very uneasy when an environmentally important area in Montana, the Flathead Valley, was facing the prospect of a mine without specific standards.

The Flathead Basin study, although concentrating its effort in the Montana portion of the basin, was constantly aware of the potential for development activities within the Canadian portion of the drainage to affect Montana. While at the same time local involvement and awareness of the study was increasing, British Columbia was unaware it was even underway.

In the fall of 1979, the Steering Committee, through former Lt. Governor Schwinden, asked for a meeting between the U.S. State Department and the Canadian Department of External Affairs. This meeting was requested so that we could make British Columbia aware of the Flathead River Basin Environmental Impact Study and we could learn about their resource management activities.

The first Canada/United States meeting on the Flathead River Basin convened on 1 August 1980. The purpose of the meeting was to provide a forum for information exchange on resource management programs in the Flathead River Basin of mutual interest to United States and Canadian resource managers. Information exchanges have since been held in 1981 and 1982. These meetings have gone beyond anyone's expectations in furthering mutual understandings on both sides of the border. Although the Flathead River Basin study has acted as a focus for discussion, a wide range of resource management activities have been discussed by representatives from both countries. Topics have included such subjects as coal mine planning, oil and gas development, smoke management, how each country is dealing with the pine bark beetle epidemic, setting water quality standards, and regional planning. Following meetings, tours have been conducted on both sides of the border. Officials from the Sage Creek Coal Company toured the Montana portion of the basin. An official from the British Columbia Ministry of the Environment spent two days learning about management objectives within the Montana portion of the basin. Montana officials have toured resource developments in British Columbia. During the summer of 1982, Governor Schwinden toured coal mines in the East Kootenays. Through the information exchanges, contacts have been established and lines of communication firmly established. Each participant has developed a better understanding of resource management in the other's country. By concentrating on data, positive similarities have been stressed as opposed to the adversarial stances often necessitated by specific development proposals.

Can information exchanges resolve the Cabin Creek coal mine controversy? The answer is perhaps, but resolving controversy is not the major goal of these exchanges. Any final resolution of the issue will rely upon the actions of both governments. What information exchanges have accomplished is communication.

Two key issues confront all transboundary issues. One: local governments lack the ability to interact with another country, yet it is the local governmental entities which are most directly affected and have the greatest understanding of the issues. Local governments' inability to act causes issues to rise to high levels of government prematurely. Although these concerns are of paramount importance locally, they tend to be considered as one of many minor disputes along the entire border. Locally the similarities on both sides of the border are striking. Nationally, the Flathead, the Poplar, the Skagit, and the Souris rivers are sources of international conflict. People in the Flathead Valley have a great deal in common with people in the East Kootenays since similar natural resources dominate local economies. These similarities do not exist when you begin to compare the Flathead with other transboundary issues. It is the similarities which can provide a basis of understanding regarding resource development objectives on both sides of the border. Information exchanges between Montana and British Columbia have proven extremely successful in providing a forum to gain an understanding of each other's objectives.

The second key issue in all transboundary issues is the problem of viewing a dispute as a single occurrence at a distinct point of time. Unfortunately or fortunately, depending upon your perspective, ecosystems do not operate in this manner and economic development is not static. They are both evolving and changing. Information exchanges provide a basis for informal discussions on the natural functioning of given areas and begin to provide a view of how each is affected by human perturbation. To be successful, this dialogue must be supported by an adequate commitment to data collection and research to provide answers to these broader ecosystem questions. The Flathead River Basin Environmental Impact Study, coupled with research in British Columbia undertaken in conjunction with planning for the proposed Cabin Creek coal mine, provided a core of data to meet this requirement. Although this level of commitment undoubtedly contributed to the success of Flathead information exchanges, resource management has advanced to the point in both countries where sufficient data exist to undertake a continuing dialogue. Ecosystem processes and an understanding of baseline conditions provide a core foundation upon which constructive dialogue can occur. Not only are data a common basis for communication, they are also a point of departure to focus on each country's major areas of concern.

If we view information exchanges as facilitators, rather than tribunals, they can serve an extremely useful role in conflict resolution. They provide a mechanism for informal local input, allow for a continuing flow of information, provide a means to begin to understand resource management processes and allow each country to obtain a better understanding of the other's objectives. Hopefully, the Flathead information exchanges will ultimately lead to the development of compatible resource management on both sides of the border. With the creation of a permanent Flathead Basin Commission, an institutional mechanism has been established to work towards this goal in the Flathead. Although the controversy surrounding the proposed Cabin Creek coal mine has not been resolved, and cannot be resolved through information exchanges, lines of communication will continue to play a positive role in the resolution of the Cabin Creek issue.

Establishment of a more comfortable working relationship through information exchanges could play a useful role in other transboundary issues. Local issues will continue to be best resolved through local involvement. Although all issues cannot be resolved through this type of involvement, at least issues can be focused for consideration at higher policy levels, whether relying upon the International Joint Commission and the Boundary Waters Treaty or some other mechanism.

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# MANAGEMENT OF INTERNATIONAL STREAMS
# - A SASKATCHEWAN PERSPECTIVE

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## ABSTRACT

International treaties and orders, monitoring boards and provincial legislation have set the rules for management of water in international river basins. The lack of direct input by the province to the determination of natural flows, differences in balance periods in interprovincial and international streams, and strict adherence to a principle without regard for equitable sharing of the water resources, have created difficulties in the management of river systems and the allocation and use of water in the Saskatchewan portion of international basins. More direct involvement by the province in international water management and adoption of the concept of equitable use of the meagre water resources of these international basins would help to resolve the problems.

## THE BASIS FOR MANAGEMENT OF INTERNATIONAL WATERS

Problems in management of the waters of streams where more than one jurisdiction is involved have probably been around for as long as there have been people who wanted to use those waters. In that respect, Saskatchewan is no different from any other jurisdiction. In order to get a better appreciation of the problems faced by Saskatchewan, it is useful to understand the legal constraints to international water management by reviewing the relevant legislation, rules and agreements.

1. The 1909 Boundary Waters Treaty - developed to prevent disputes regarding the use of boundary waters, settle related outstanding water resources questions involving the rights, obligations or interests of either Canada or the United States, and make provision for the adjustment and settlement of questions which may arise in the future.

2. IJC Order on the St. Mary-Milk Rivers - issued October 4, 1921, to spell out conditions of apportionment of the two rivers and the Eastern tributaries of the Milk River.

3. International Souris - Red Rivers Engineering Board - established in 1948 to investigate and report on water requirements

on projects between the Milk River basin and the Red River of the north.

4. International Souris River Board of Control - created in 1959 to ensure compliance with the approved interim order.

5. Transfer of Natural Resources to Saskatchewan - finalized in 1930 to give control of natural resources to the province.

6. The Master Agreement on Apportionment - signed in 1969 to establish apportionment criteria for interprovincial streams.

## PROBLEMS IN MANAGEMENT OF INTERNATIONAL WATERS

### Souris River

Problems with apportionment in the Souris have been minimal. The Board of Control meets twice annually - in May to ensure that all conditions of the 1958 Interim Order can be met, and in January to make the final flow calculations and prepare the annual report.

The only major problem currently of concern to Saskatchewan is the makeup of the Board. Although Saskatchewan is responsible for administration of its water resources, the Board has only two members - one from Canada and one from the United States. Saskatchewan has been granted observer status on the Board but this is a weak role at best. The fact that the problems have been minimal is due in large part to the low level of water resource development relative to the runoff and the distribution of the runoff. These have combined to minimize the requirements to "manage" the water to meet the terms of the Interim Order. With increasing development, this situation is certain to change and Saskatchewan sees a need for direct input to Board functions.

### Poplar River

Concurrent with the construction of a reservoir on the East Poplar River, to provide cooling water for a new power plant in Saskatchewan, a Task Force on apportionment recommended in 1976 that the entire Poplar River basin be treated as a single basin. On the East Poplar maintenance of a certain continuous flow across the boundary was recommended plus provision for Saskatchewan to store a block of water for later release on demand by Montana. The rate of continuous flow and the amount of the demand release were to be dependent on the size of the runoff each year. On the Middle Poplar, the recommendation called for Saskatchewan to deliver a minimum of 60 per cent of the natural flow at the United States boundary and on the West Poplar River and all other tributaries, it was recommended that the natural flow at the United States boundary not be depleted by more than 60 per cent.

The Task Force also recommended that a six-member Board of Control be named to oversee the apportionment. Saskatchewan would nominate one of the Canadian representatives.

While the apportionment recommended has not been formally adopted, it has been generally followed since being recommended in 1976.

The continuous release requirement has not posed a problem for Saskatchewan during that period. However, problems arise with the recommendation for release from storage which may be demanded by Montana at any time in the twelve-month period up to June 1 in the year following the runoff. In fact, two years of the storage could be demanded in one year - the component from the previous year could be demanded in May and the allotment for the current year could be demanded in June. If the first year in the cycle was a high runoff year and the second year a low runoff year, Saskatchewan could be required to release a large quantity of water in a year when little or no runoff occurred. This is an entirely possible sequence and one which would place a severe restriction on the operation of the Cookson Reservoir at Coronach for cooling water purposes - the very reason it was built in the first place.

The recommendation for a six-member Board of Control is compatible with the Saskatchewan approach in that it provides for the jurisdiction responsible for control of the resources to have direct input to the monitoring of and compliance with the apportionment of that resource.

## Eastern Tributaries of the Milk River

The IJC Order of 1921 with respect to the eastern tributaries of the Milk River provides a different set of problems. That order specified that "The natural flow of the eastern . . . tributaries of the Milk River at the points where they cross the international boundary shall be divided equally between the two countries." For practical reasons, a 10-day division period has been established.

Saskatchewan has three basic problems with the apportionment of these streams:

1. The province has no direct input to the monitoring, development of procedures and calculation of the natural flows.

2. The province receives no credit for surplus deliveries to the United States.

3. The interprovincial Apportionment Agreement places a heavy burden on Saskatchewan.

Monitoring of the IJC Order is carried out by an Accredited Officer for each country. Unlike the Souris and Poplar basins, no Board arrangement exists. Although the province is responsible for directing operations to ensure apportionment is met, the province has no input to the monitoring and no input to determination of the natural flows used to derive the Canadian and United States shares of water. However, when problems arise and local people become concerned over the application of the Order, Saskatchewan is expected to defend the action taken.

The matter of deficits and surpluses is also of concern. Deficit deliveries are accumulated and must be made up - usually as soon as possible. Surplus deliveries do not accumulate so that each 10-day division period starts either in balance or in deficit. The rationale for this approach is unclear - but it is clearly a problem for Saskatchewan since to make sure the Canadian commitment is met over-deliveries are often made. The approach seems to be imcompatible with Article VIII(b) of the 1921 Order which requires the Officers "To operate the irrigation works of either country in such a manner as to facilitate the use by the other country of its share of the said water . . . to secure to the two countries the greatest beneficial use thereof."

The requirement to make up deficits without getting any credit for surpluses does not match Saskatchewan's concept of "beneficial use" in the two countries.

Interprovincial apportionment is a problem which must be resolved by Alberta and Saskatchewan. However, it is noted that the present interprovincial division of water is on an annual basis whereas the international balance period is 10 days. Frequently, Saskatchewan has to make up the entire Canadian share of water to be delivered to the United States.

## SOME POSSIBLE SOLUTIONS TO INTERNATIONAL PROBLEMS

These problems are not new and many solutions have been proposed over the years. Since the problems still persist, either the solutions were not tried or they failed to resolve the issues.

The main solutions which come to mind are:

1. Develop New Administrative Arrangements

   Good communications is one way of minimizing problems. Saskatchewan believes that communications would be greatly improved if the province assumed a more direct role both in monitoring of apportionment and calculation of natural flows through membership on the monitoring Boards. For the Souris, a proposal has already been taken to the IJC for consideration. In the case of the Milk River tributaries, no monitoring Board exists and Saskatchewan feels consideration should be given to restructuring the present Accredited Officers arrangement to allow the province direct contact between Saskatchewan and Montana water managers.

2. Define Equitability in the Division of Water

   The concept of beneficial use of water should assume greater importance in apportionment. Release of water by Saskatchewan just to satisfy an apportionment formula - even if the United States interests don't require the water - cannot be construed as "beneficial" use of water. Likewise, it is difficult to justify as beneficial the release of water from a Saskatchewan reservoir a year after it was stored if it results in a shortage to Saskatchewan. The term "equitable" has found frequent use in administration of interprovincial waters. It is a term that could find equal favour if adopted by the administrators of international waters.

3. Commit Financial Resources to Resolution of Apportionment Problems

   Physical works are certainly not the answer to all water management problems. Nevertheless, in some circumstances extraordinary measures must be taken to ensure that the maximum amount of water is made available for use. In an extremely water-short area like south-west Saskatchewan, any actions which will conserve water for local use must be given serious consideration. Storage near the boundary to meet international commitments would significantly reduce conveyance losses, eliminate over-deliveries and ensure that deficits did not become a problem for the upstream jurisdiction. As well, deliveries could be made at a time when they would be of more value to the downstream jurisdiction. These benefits would be partially offset by evaporation from the storage created.

   Improved monitoring would also be of benefit to the water managers. The Canadian Inland Waters Directorate makes a significant effort to obtain the timely information necessary to make decisions on operations to meet international commitments. Nevertheless, additional resources directed toward improving the monitoring network by adding additional hydrometric stations and more manpower to provide real-time data more frequently during critical runoff periods would be of considerable value in resolving many of the operational problems which exist.

In summary, the management of international streams presents special problems for water managers. These problems are of particular concern to upstream jurisdictions such as Saskatchewan which has no streams which flow from the United States to Canada. An upstream jurisdicition can never fully receive its legal entitlement under an apportionment agreement - it's simply not physically possible. However, steps can and must be taken to overcome problems. As the water resources in the upstream jurisdiction become heavily developed and the competition for water intensifies, water users refuse to accept anything less.

# TRANS BOUNDARY RELATIONS

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## ABSTRACT

In spite of many geographic and cultural similarities between citizens of the prairie provinces and states, government agencies tend to polarize differences when trans-boundary disputes arise. Local governments on both sides of the border attempted to solve flooding problems of the Pembina River in different ways, which led to recurring controversy. When the International Joint Commission (IJC) declined to review the problem, states and provinces formed committees to work toward a solution. This has culminated in the recent creation of the North Dakota-Saskatchewan Boundary Advisory Committee, which is made up of legislative and executive officials. It is hoped that similar arrangements can be made between Manitoba and North Dakota. The Committee's function is to improve communication and prevent escalation of controversies to federal levels.

This paper represents the views of one person -- a non-expert -- who lives on the south side of a legally described, 6415 km long line that runs through or crosses over water for 50 percent of its length and is commonly known as "the International Boundary," "the Canada-United States Border," or perhaps, just "the Line."

As I began thinking about communication processes involved in relations between Canada and the United States, I decided that it might be helpful if I were to make a list of the major differences that exist. What important elements make communications between the two countries different?

Geography? Geology? Weather& Soils? Obviously, we have more simiilarities than differences as our land masses are about the same age and have undergone the same kinds of changes over time.

Languages? Religions? Customs? Both countries were settled by Europeans, so there are no great differences in the way or the general manner in which our peoples live and relate to each other as communities or groups. Each country has metropolitan and rural areas, each has neighborhoods or communities where customs of the past are important elements of the present way of life, and each has a thriving agricultural, business and industrial complex upon which the national economy is built.

If the two nations have so many similarities what are the great differences that frequently make trans-boundary relations difficult?

Undoubtedly, each of us would answer this question from the standpoint of long experience. My answer, based on my experience, is that GOVERNMENT is the root of many problems. Not any particular kind or philosophy of government, just government in all its complexities, its protocol, its never-ending exchange of notes, letters and greetings, and its layers of bureaucratic departments!

There appears to be no way in which a problem can be addressed and solved with dispatch at the local levels of government. Every issue seems destined to wind up in a file in the United States Department of State or in the Canadian Department of External Affairs. Procrastination is a management tool that is employed extensively by both governments and, if a problem persists in spite of the best use of this management tool, the International Joint Commission is asked to study it and recommend solutions.

I consider the IJC to be the most effective entity available to the two countries for the settlement of boundary waters disputes. Unfortunately, this board becomes involved only as a last resort after various municipal, county, provincial and state groups have spent months and years studying problems. Once involved, the IJC has performed remarkably well and has earned the respect of officials and agencies on both sides of the border.

For the purposes of this paper, let us accept the premise that the IJC is an effective entity in recommending solutions to problems that have been referred to it.

What happens to those problems which, for one reason or another, are not accepted for study by the IJC, or have not been referred to it by appropriate governmental actions?

In northeastern North Dakota, the Pembina River flows into the state from Manitoba, falls swiftly down the escarpment created by the Pembina Hills, then snakes its way across the flatland of the Red River Valley before emptying into the Red River just south of the International Boundary. In high-flow years, the river leaves its banks as it reaches the valley floor and floods thousands of hectares of fertile valley lands in both countries.

After several years of study, the two federal governments proposed the construction of two impoundments on the Pembina River, one in Manitoba and the other in North Dakota. Subsequently, Canadian planners decided against a dam north of the border. Planning continued for the development of the Pembilier Dam, the name given for the North Dakota project.

Meanwhile, the damaging flood of 1950 occurred. Up to 16,000 hectares of valley lands were inundated, as were several communities in both countries. Receding waters eroded huge trenches across the rich farmlands.

Landowners and local units of government, tired of waiting for the federal governments to act, marshalled their forces and constructed some works in anticipation of further flooding. On the south side of the border, this work consisted of diking projects along both sides of the Pembina River to prevent spillout between the escarpment and the Red River.

The Canadians, fearing that this diking work would increase flooding depths when failures occurred, began the construction of a road paralleling the border across the width of the valley. Very small culverts were placed in this road where north-flowing drainage channels crossed the border. Needless to say, this "road-dike" aroused the ire of the Pembina County farmers, local officials, and citizens in general.

State and provincial meetings were held on numerous occasions during the 1950s and 1960s, and several floods occurred during which potentially serious border confrontations took place. Manitoba refused to remove or modify its road-dike and during floods it was mysteriously breached at strategic places in spite of well organized dike patrols.

In the late 1960s, federal officials on both sides of the border became alarmed at the increasing intensity of the confrontations taking place across the dike and requested assistance from the International Joint Commission. For reasons that were never fully explained, the IJC decided this matter was not within its purview and refused to consider it.

In 1971, Manitoba and North Dakota formed an Ad Hoc Committee to work toward solution of the problems. This Provincial-State Committee had representatives from Canadian External Affairs and the United States Department. Local governmental officials also joined in the meetings.

Flooding, fighting, and meetings continued until December 1976, when the meetings were discontinued as a result of the adoption of a Memorandum of Understanding signed by all parties. This agreement called for the border dike to be modified at all crossings so that agricultural flows across the border could be accommodated. Sections of the dike exposed to Pembina River overflows would not be modified until the Pembilier Dam was in place.

Since 1976, when agreement was reached and forwarded to External Affairs and State Department, there have been several letters exchanged, several briefings of new officers who move into Foreign Affairs chairs in Ottawa and Washington, and several very serious floods. Also, the United States Corps of Engineers has had second thoughts about construction of Pembilier Dam and is now considering a by-pass floodway which pleases nobody locally.

This border dike problem is an example of what happens to the problem-solving process when the IJC chooses not to become involved in a dispute. Situations of this sort will occur because of the rapidly increasing number of requests made for IJC involvement.

The majority of incidents requiring formal bi-national agreements occur in the Great Lakes area, and relatively few IJC agendas have involved problems in the prairie states and provinces. I believe this situation will change and that there will be an increase in the potential for friction along the border in the prairie country.

This increase will come about as the two nations intensify development of the area. Each views this area differently. Canadian commercial and industrial expansion undoubtedly will occur in the southern areas of each province because of the existence of transportation and municipal facilities necessary for development of their resources. The labor pool and service facilities are in place in these areas.

States south of the border tend to view border areas as being suitable for recreational and open-space so there has been limited development of transportation facilities with smaller population growth. Industrial and commercial development has been established, for the most part, considerably south of the border.

As each nation's population continues to increase, these two dissimilar development philosophies will create friction which, without effective communication across the border, will increase to a point where it will require the attention of that already overworked entity, the International Joint Commission.

It makes good sense to think in terms of developing an informal communications mechanism to consider points of contention before they become full-scale controversies. Effective communication between provinces and states will inevitably lead to a better understanding of the manner in which each functions, and could lead to cooperative endeavors which will benefit all parties involved.

Premier Grant Devine of Saskatchewan and Governor Allan Olson of North Dakota met in Bismarck last December to consider a cooperative approach to the consideration of mutual problems and opportunities. From this meeting came the idea for the creation of a North Dakota-Saskatchewan Boundary Advisory Committee. Governor Olson and Premier Devine will be co-chairmen of this group of legislators and executive branch officials who will meet upon call to consider matters of mutual concern.

The North Dakota legislature unanimously approved legislation establishing the committee and nominated five legislators and five executive branch officials to represent agriculture, water resources, economic development and tourism, and environmental protection concerns. Saskatchewan has named its membership, but no firm arrangement has been made with Manitoba, although it is hoped that this will be accomplished in the near future. A tentative date for an organizational meeting has been set.

While the people of the prairie states and provinces share many common interests and a similar way of life, there are differences in their development philosophies and governmental structures which can lead to misunderstanding and, on occasion, controversy and confrontation.

The International Joint Commission appears to be the only effective mechanism for dealing with confrontation and it has a workload problem, particularly with its heavy involvement in the matters associated with relationships across the border in the Great Lakes area. There is nothing to indicate that this involvement will be decreasing in the future.

Premier Devine and Governor Olson believe that the Boundary Advisory Committee will be an important part of future provincial-state relations and that its most important function will be its ability to improve communications between the two entities. It is possible that it can do more to develop solutions to problems before they become controversies requiring the attention of the federal governments and the International Joint Commission.

I look forward to being a part of this group and to working toward the development of our common interests and an understanding of our differences.

# POLICIES RELATED TO TRANSBOUNDARY WATER ISSUES: A CANADIAN PERSPECTIVE

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## ABSTRACT

On the Great Plains, Canada and the United States share portions of two major drainage basins: the Missouri River Basin and the Saskatchewan-Nelson Basin. The interruption of natural basin boundary configurations by a straight political boundary line has presented some interesting problems. Surface and groundwater movements generally continue to follow natural patterns, though they are now regulated in many ways on both sides of the international border. To date, no artificial disruption of the major basin boundary has occurred. Water management issues of the day are a mixture of old (e.g. Milk River apportionment), recent (e.g. Poplar River thermal power plant), and potential (e.g. water export).

In Canada, management decisions are guided by policies at a variety of levels. Perhaps the most fundamental is the policy regarding observance of the Boundary Waters Treaty of 1909. Since 1912, Canada has agreed with the United States on the issuance of 61 Applications and 48 References to the International Joint Commission. Other policies relate to federal/provincial activities and relationships, to industrial development, water development projects, and environmental assessment procedures.

Of particular recent interest are two "pillar" policies of Environment Canada: an Environmental Quality Policy, and an Environmental Conservation Policy. A new federal water strategy is expected to be announced in mid-1983.

The status of provincial policies is mixed. Alberta has published a policy statement, but Saskatchewan and Manitoba have not produced formal consolidated policy documents.

The implications of formal policies and those that can be inferred, are discussed in the context of foreseeable issues.

# INTERNATIONAL COOPERATION IN WATER RESOURCES DEVELOPMENT

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## ABSTRACT

Montana and the provinces of British Columbia, Alberta, and Saskatchewan have a unique relationship in which cooperative management of natural resources is crucial to the welfare of individuals and the economic prosperity of the region. While much has been accomplished within the confines of cooperative water resources management, this spirit of working together, friendship and trust must be sustained. Five resource management issues are identified where continued cooperation between the states and provinces has been, and will continue to be, mutually beneficial.

## INTRODUCTION

The state of Montana is unique and privileged in that it is the only state which shares its boundaries with three Canadian provinces: British Columbia, Alberta, and Saskatchewan. Montana shares similar lifestyles and resources with each of these provinces. Indeed, we are rich in a number of natural resources and our economies and future well-being are dependent on the cautious development and wise use of these resources.

Tourism and recreation are important industries to both areas. The Alberta-Montana boundary bisects a system of glacial parks of international stature. Backpacking and canoeing are popular activities along the Boundary Waters and, in 1988, Calgary and Banff will host the Winter Olympics.

Agriculture is of prime importance both north and south of the 49th Parallel. Water is life in the West, and agriculture is predicated on the availability of an adequate water supply, either from free-flowing rivers or from stored water in reservoirs.

Finally, major sectors of both state and provincial economies are engaged in the mining of minerals, the harvesting of timber, and the processing of oil and natural gas.

The importance of an adequate supply of high quality water for agriculture, recreation and industry cannot be overstated. For this reason, the present attitude of international cooperation in water resources management and development must continue. To this point, our track record together has been good, and the state of Montana remains committed to preserving these good relations and open dialogue with our neighboring Canadian governments.

Before discussing some of the issues which are relevant to transboundary water management, I would first like to outline the major river systems, and the treaties or formal agreements that affect them.

### Montana-British Columbia

Two major rivers cross the international boundary between Montana and British Columbia: the Kootenai and the North Fork of the Flathead. While no specific water apportionment or formal allocation covers the North Fork of the Flathead, it does fall under the jurisdiction of the 1909 Boundary Waters Treaty. The United States and Canada entered this treaty for the purposes of protecting navigation, streamflow, and water quality. The 1909 treaty also created the International Joint Commission (IJC) whose purpose is to preside over any international water disputes that are referred to it.

The Kootenai River was included in the Columbia River Treaty which was ratified by the federal governments of Canada and the United States in January, 1961. The treaty promotes cooperative development of water resources in both countries for the purposes of hydroelectric power generation and flood control. Construction of Montana's Libby Dam and Canada's Duncan Lake project are the direct result of the Columbia Treaty. Rules and regulations which outline reservoir operation principles, and a process for determining hydroelectric power generation benefits, are contained in the treaty's appendixes.

### Montana-Alberta

The Kootenai-Waterton River, Belly River, St. Mary River, and Milk River are the most significant rivers crossing the international boundary between Montana and Alberta. The St. Mary and Milk rivers were apportioned in Article VI of the Boundary Waters Treaty and, in 1921, the International Joint Commission issued an order which clarified the apportionment and laid the groundwork for actual water administration. The 1921 order apportions natural flows on a percentage basis only when the flow at the point of measurement falls below a specified threshold.

### Montana-Saskatchewan

The two main rivers that flow across the international border between Montana and Saskatchewan are the Big Muddy and Poplar. The Big Muddy is not presently covered by a treaty or formal agreement other than that which is provided in the 1909 Boundary Waters Treaty. In 1978, the International Joint Commission made a recommendation regarding the apportionment of water from the three forks of the Poplar river, although to date this recommended apportionment has not been formalized in treaty form. This issue is important to the state of Montana, and one which I would like to address in more detail later during the presentation.

## IDENTIFICATION OF WATER ISSUES WHERE STATE-PROVINCIAL COOPERATION CAN BE MUTUALLY BENEFICIAL

Joint water resources planning first at the state and provincial level, rather than at the federal level, is mutually beneficial to both parties. Historically, planning at the state-provincial level has been very productive. This may be true for a number of reasons. First, Montana and the provinces have more in common concerning specific water issues than do their respective federal governments. State and provincial officials are usually more familiar with local concerns. Second, matters of national prestige sometimes can separate our federal goverments. The great debate over acid rain is a good example of this. Problems of this nature might best be resolved first between the state and province before seeking involvement and cooperation from our federal governments.

During the remainder of this discussion I would like to outline and describe five of the most significant transboundary water management issues requiring our attention today. They are:

1. The need for joint water management in the St. Mary-Milk River basins.
2. Finalization of the IJC 1978 Poplar River recommended apportionment.
3. Analysis of the Cabin Creek Coal Mine environmental impacts.
4. Management of saline-seep.
5. Regional groundwater management of the Ancestral Missouri River channel.

### Joint Water Management Plan in the St. Mary and Milk River Basins

The headwaters of the Milk River begin near Glacier National Park located in northwestern Montana. The Milk then flows northeastwardly through the Blackfeet Indian Reservation, crosses the international boundary just east of the port of Del Bonita and meanders its way through Alberta for approximately 62 km. From there it loops back into Montana where it eventually joins the Missouri. The Milk provides inflow to Fresno reservoir and also forms the northern boundary of the Fort Belknap Indian reservation.

Water apportionment on the Milk River is based on paragraph II of the 1921 Boundary Waters agreement. Paragraph II divides water on a 50-50 basis according to a calculated natural flow at what is commonly referred to as the "Eastern Crossing." The natural flow is quite variable and ranges from floods of over 283.2 $m^3$ per second to lows that are practically zero.

In the past, Alberta has seen serious water shortages for irrigation and stock watering uses. This is largely because the Milk River in Alberta has no reservoir storage. In light of this problem, a need for storage on the Milk River was first voiced in 1977 by a group known as the Milk River Water Users Association. The Association requested Alberta Environment to examine a number of alternatives to insure a firm water supply along the Milk. As a result of that request, five potential reservoir sites have been studied.

The flow of the Milk River from Canada into the United States has always been greater than the quantity of flow needed to satisfy the 1921 Boundary Waters agreement. In spite of this, and the fact that Milk River flows are augmented by a transbasin diversion from the St. Mary River, Montana irrigators have experienced water shortages approximately every four out of ten years. This situation would be exacerbated if Canada diverted its legal entitlement, or the Fort Belknap tribes developed their reserved water right without first creating additional water supplies.

The State of Montana, the Milk River Irrigation Districts, and the Bureau of Reclamation are now in the process of evaluating different options for solving the present and projected water shortage problems on the Milk River. One option is to divert water from the Missouri River mainstem or from Tiber Reservoir on the Marias River into the Milk River. Another option is that of increasing the capacity of the St. Mary-Milk diversion. A joint reservoir project in Alberta interests Montanans and Albertans alike because this alternative appears to mitigate potential environmental conflicts and optimizes water use for both state and province.

As the water planning proceeds, whether in Alberta or Montana, it is crucial to have continuing discussions on those concerns and issues that affect each nation's economy, environment, and institutions. As we share the river, we must also share a common planning agenda that promotes cooperative management of water resources in the Milk River Basin, as well as the projects that accomplish our common objectives.

## Finalization of the 1978 Poplar River Apportionment Recommended by the IJC

The three principal branches of the Poplar River (West Fork, Middle Fork, and East Fork) all originate in Southern Saskatchewan. The Middle and East Forks meet north of Scobey, Montana, and later join the West Fork on the Fort Peck Indian Reservation. The main stem continues southward and enters the Missouri River near the town of Poplar, also on the Fort Peck Reservation.

In 1978, the International Joint Commission published a recommended apportionment for the transboundary flows of the Poplar River which is based on a thirty-year-old reference from the governments of Canada and the United States. Twenty-two alternatives were analyzed before the final recommendation was endorsed. This final recommendation considered each of the three tributaries individually. The flows were apportioned in such a way as to minimize the costs of monitoring and simplify the procedure for water administration. The aggregate effect of the recommended apportionment is to divide the natural flow of the Poplar River equally between Saskatchewan and Montana. This division is subject to a number of limitations. These limitations provide for a live stream and for the protection of existing irrigation.

Public hearings were held regarding the adequacy of the recommended apportionment. Factions in both Saskatchewan and Montana were not entirely supportive, and expressed concern over "how much their side had given up." I would imagine that this may be the best indication we have that the Poplar apportionment is fair and reasonable to both sides.

Since 1978, there has been excellent cooperation between state and provincial government agencies which have voluntarily complied with the recommended apportionment. Instream requirements and channel flushing flows have been released from Cookson Reservoir according to this apportionment. This history of cooperation in the Poplar basin has resulted in other benefits, including the exchange of snow survey information, flood forecasting, and a certain amount of flood protection.

The state of Montana feels that the IJC recommended apportionment of 1978 is reasonable and fair. Any strategy for cooperative resource management in the Poplar basin should include formalizing this recommended apportionment into a treaty.

## The Cabin Creek Coal Mine

The proposed Cabin Creek Coal mine is an issue of international concern because of the potential impact on water quality, endangered species, air quality and fish habitat. Ron Cooper, Director of the Flathead River Basin Environmental Impact Study has already spoken with us concerning many of the details of the Cabin Creek project.

The importance of cooperation in planning a study of this nature is exemplified by the informational exchange meetings that have been held between officials in British Columbia and Montana, including the Flathead Basin Environmental Study team. The provinces are to be commended for listening to our concerns and reflecting upon these concerns in the decision-making process.

## Management of Saline-seep

Saline-seep is a water and land-related resource conservation problem facing the northern plains of the United States and the prairies of Canada alike. Thirty-five years ago, it was not even recognized as a problem but, today, it has reduced our productive land base by more than 0.8 million hectares. Aside from this loss of arable land, seep is responsible for the deterioration of many surface and shallow groundwater resources.

Saline-seep is a process which may be traced to certain land management practices; specifically the use of alternate crop/fallow dryland farming methods. Cultivation of prairie soils destroys the columnar soil structure and natural plant root pathways, which allows excess water to percolate downward beneath the root zone and pick up high concentrations of soluable salts. This poor quality water continues its downward movement until it reaches a zone of impermeable material, such as clay or shale, where it then moves laterally. When it reaches a zone of discharge, it evaporates and leaves high concentrations of salt deposited on the surface.

Resource management alternatives that mitigate the causes of saline-seep are being explored by many agencies in Montana, including the Montana Bureau of Mines and Geology, Montana State University, the Soil Conservation Service, and the Department of Natural Resources and Conservation. In addition, the Triangle Conservation District received funding from the 1979 Montana legislature to provide technical assistance to farmers in order to implement saline-seep control practices. This program has been an overwhelming success and may soon be applied on a watershed wide basis.

In March of this year, Montana and Alberta entered into a memorandum of understanding to facilitate State-Provincial cooperation in research and control of dryland salinity. The objectives of this understanding are:

(a) to exchange research information, techniques and expertise;
(b) to exchange technical bulletins, and any other extension means for the benefit of all involved;
(c) to increase the depth of investigation possible in selected projects;
(d) to promote a more coordinated State-Provincial effort in research and implementation of salinity control programs;
(e) to encourage farmers as individuals, groups or associations to foster dryland salinity control projects and programs.

In cooperation with the Triangle Conservation District and the Dryland Salinity Control Association of Alberta, we feel the memorandum of understanding contributes to the strong liaison between Montana and Alberta in dealing with the problem of saline seep.

## Regional Groundwater Management and the Ancestral Missouri River Channel

The ancestral Missouri River channel is an alluvial stream bed of the ancestral Missouri River that was buried by glacial debris during the Pleistocene age. Prior to Pleistocene glaciation the Missouri River flowed in a more northeasternly direction through parts of Montana, North Dakota, Saskatchewan, and into Manitoba where it eventually emptied into Hudson Bay. The alluvium is primarily composed of pebbles, gravel, and boulders. Wells drilled into this formation often produce as much as 3630 l per minute. North Dakota has conducted significant research on the subject of the ancestral Missouri and, more recently, the Montana Department of Natural Resources, the Bureau of Mines and Geology, the Sheridan Conservation District, and the Fort Peck Tribe initiated further study. The objective of this study is to learn more about the aquifer's configuration, ultimate productivity, and available storage.

Present evidence reveals that the only sources of recharge to the aquifer are precipitation in the form of rain or snowmelt, and ground water leakage to the aquifer from the Fort Union formation. A naturally slow rate of recharge indicates that we need to protect the aquifer from overdevelopment. This is especially true where heavy pumping during the summer irrigation season could induce recharge from Big Muddy Creek and subsequently lower water quality to unacceptable levels. In addition, increased drawdowns mean greater pumping costs.

Overdevelopment could seriously impact the Medicine Lake Wildlife Refuge. The ancestral Missouri River channel runs just beneath this national waterfowl refuge and designated wilderness. Any drawdown in the vincinity of this refuge could lower the water table and destroy the refuge.

The ancestral Missouri River channel aquifer is an issue of mutual concern to the United States and Canada since the aquifer crosses state and international boundaries. Pumping of ground water in one political jurisdiction can cause significant drawdowns in another. Accordingly, those in the United States and Canada who use this ground water resource need to do so in a wise and cautious manner. Our cooperation in the development of a regional management plan for the ancestral Missouri aquifer is an issue with which we should all be concerned.

## CONCLUSION

In conclusion, I would like to stress the importance of cooperation and working together in order to solve transboundary water related problems. An open dialogue and liaison must be maintained even though governments may change. By cooperating, we may take advantage of many opportunities including the exchange of technical information, the cultivation of international relations, and the most efficient management of communal resources.

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